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STRUCTURE, STRATIGRAPHY AND EVOLUTION OF CENTRAL MEDITERRANEAN

Summary. The purpose of this paper is to outline the regional structure, stratigraphy and evolution of the Pelagian and Ionian Seas. Information, descriptions, remarks, ideas and conclusions here reported are based on a great amount of new geological, geophysical and drilling exploration data, and on the numerous most informative published scientific papers.

The studied area has been schematically subdivided into geological provinces according to their relevant regional characters. Every province is described in a synthetic manner regarding stratigraphy, structural setting, main geodynamical phases, which have occurred and associated regional volcanic activities.

Four principal extensional phases are recognized from Permo-Triassic to Quaternary. The first one, active during Middle-Upper Triassic, produced a continental rifting with prominent effects in the Gabes-Tripoli-Misurata basin, Steppenosa Trough (Sicily-Malta platform area), Sicily-Malta-Medina Mounts and Medina Bank areas, and in the Ionian Sea. The second extensional phase occurred in Middle-Jurassic and opened the Ionian Sea. The Sicily-Malta escarpment is affected by an extensional mega-fault system that connects the thick continental crust of the Pelagian Sea to the paleo-oceanic crust of the Ionian abyssal basin.

The Pelagian Sea and Sirte rise (excluding the Upper Sirte Slope, where sedimentation commenced in the Upper Cretaceous), are constituted by a more or less thick sedimentary sequence that includes depositions from Triassic to Quaternary. The Sirte Rise, as well as other geological provinces of the studied area, was greatly stretched during the third extensional phase of the Middle Upper Cretaceous.

The Ionian abyssal basin is interpreted as a paleo-oceanic crust which has been continuously covered by deep water sediments from the Middle Jurassic to Quaternary. In the central part of the Ionian, where there exists the maximum Bouguer anomaly of the Mediterranean, the sedimentary sequence as well as the lower crust, are considerably thinner.

The last main extensional phase occurred from the Middle-Upper Miocene to Quaternary and affected the greater part of the Pelagian and Ionian Seas, but in particular the areas of Malta-Pantelleria-Linosa, Medina Grabens and the Ionian Sea. Malta Islands are structurally an horst which emerged in the Pelagian Sea during late Miocene-Lower Pliocene. The rifting process of the Pelagian Sea involves the entire median area known as the Sicily Channel with numerous extensional faults, block collapsing, tilting and widespread volcanic activity.

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1. Introduction

After more than two decades of intense geological and geophysical exploration activities, remarkable progress has been made in the knowledge of structure and stratigraphy of the Mediterranean. This does not mean that all aspects of the basin are now fully understood. But it is today possible to propose schemes of geodynamical evolution supported by more data. In addition to the scientific investigation, a consistent contribution has been made also by the oil exploration activity on the

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continental shelf areas. Drilling results of the JOIDES project in deep waters are also very important, especially for the study of the Messinian and Plio-Quaternary series.

In the present paper, the Author outlines the regional stratigraphic and structural conditions of the Central Mediterranean (Pelagian and Ionian Seas) mainly resulting from interpretation of the seismic exploration conducted by OGS, or published, or available. Moreover some major extensional phases, associated volcanic activities, and subsidences are recognized and described.

Careful analyses of the great amount of collected data allow the existence of an old oceanic crust in the abyssal plain of Ionian Sea to be deduced. The geological interval of time of crustal opening and evolution of such a basin are also proposed.

The investigation is extended also to the southern Apulian platform area which is considered as a plate separated from the African megaplate during the crustal opening of the Ionian Sea.

An important contribution to the understanding of the geodynamical movements of the studied area is given by the reconstruction of the volcanic activities which have occurred during various phases from the Triassic to the present time.

Significant contributions to the enhancement of knowledge were furnished by the drilling exploration activities of Glomar Challenger (D.S.D.P.; Legs 13 and 42 a); Ryan et al., (1973); Hsü et al., (1978).

It has been clear for several years that the Ionian Sea is a key area for the observation of important geological events, determinant for the understanding of the evolution of the Central-Eastern Mediterranean. For this reason many Authors were attracted to the exploration of this basin.

After the discoveries of the relevant data in support of the plate tectonics theory in the Atlantic ocean and its margins, the first general attempt to introduce a plate tectonic model in the whole Mediterranean, to explain the evolution of this basin, was carried out by Dewey et al., (1973). The Authors of this paper were of the opinion not only that the history of the Mediterranean and Alpine system is basically associated with the opening of the Atlantic and relative plate movements between the Americas and Europe-Africa, and between Africa and Europe, but also that the fundamental plate tectonic models, developed at that time, were valid for the Mediterranean area. It is to be said that at the time of publication of this paper the exploration and knowledge of the Mediterranean was much more scarce than some years later. For this reason the Authors had not the opportunity to take into consideration some important data and aspects observed by successive explorations, but they had the merit to believe in the plate tectonic models for the Mediterranean, even if at that time the Authors favourable to such an interpretative approach were not numerous.

Boccaletti et al., (1972; 1974; 1976) applied progressively the interpretation model of Marginal and Back-arc basin to the Ligurian Sea and Apennines and, at the end to the entire Mediterranean area.

Biju-Duval et al., (1976; 1977) proposed a plate tectonic model based on the kinematic evolution of the african and European plates given by Pitman and Talwani (1972), and using the rotation suggested by Francheteau (1973), for the relationships between Africa ad North America. This interesting model takes into account a very consistent number of observations and considers a more limited number of plates than Dewey et al., (1973).

Laubscher (1971; 1973; 1974) and Laubscher and Bernoulli (1977), examining the Central-Western Alps, the Dinarides and Hellenides, propose plate tectonic models having some original modifications with respect to the classic schemes. These Authors emphasize the palinspastic reconstructions and consider gravity as the main driving force in the subduction process. The model which postulates a southern origin of

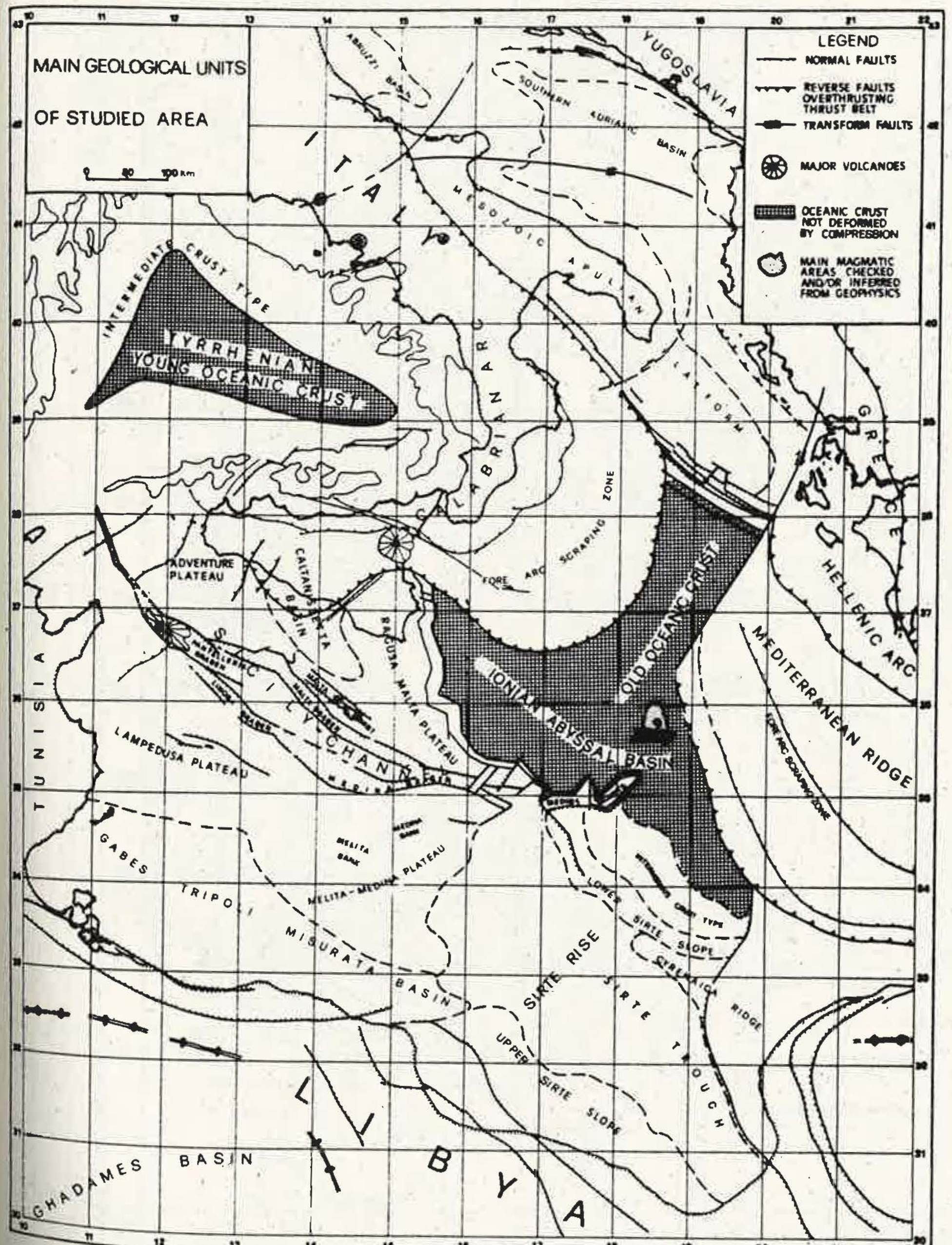


Fig. 1 — *Studied Area of Central Mediterranean and Scheme of Geological Subdivision.*

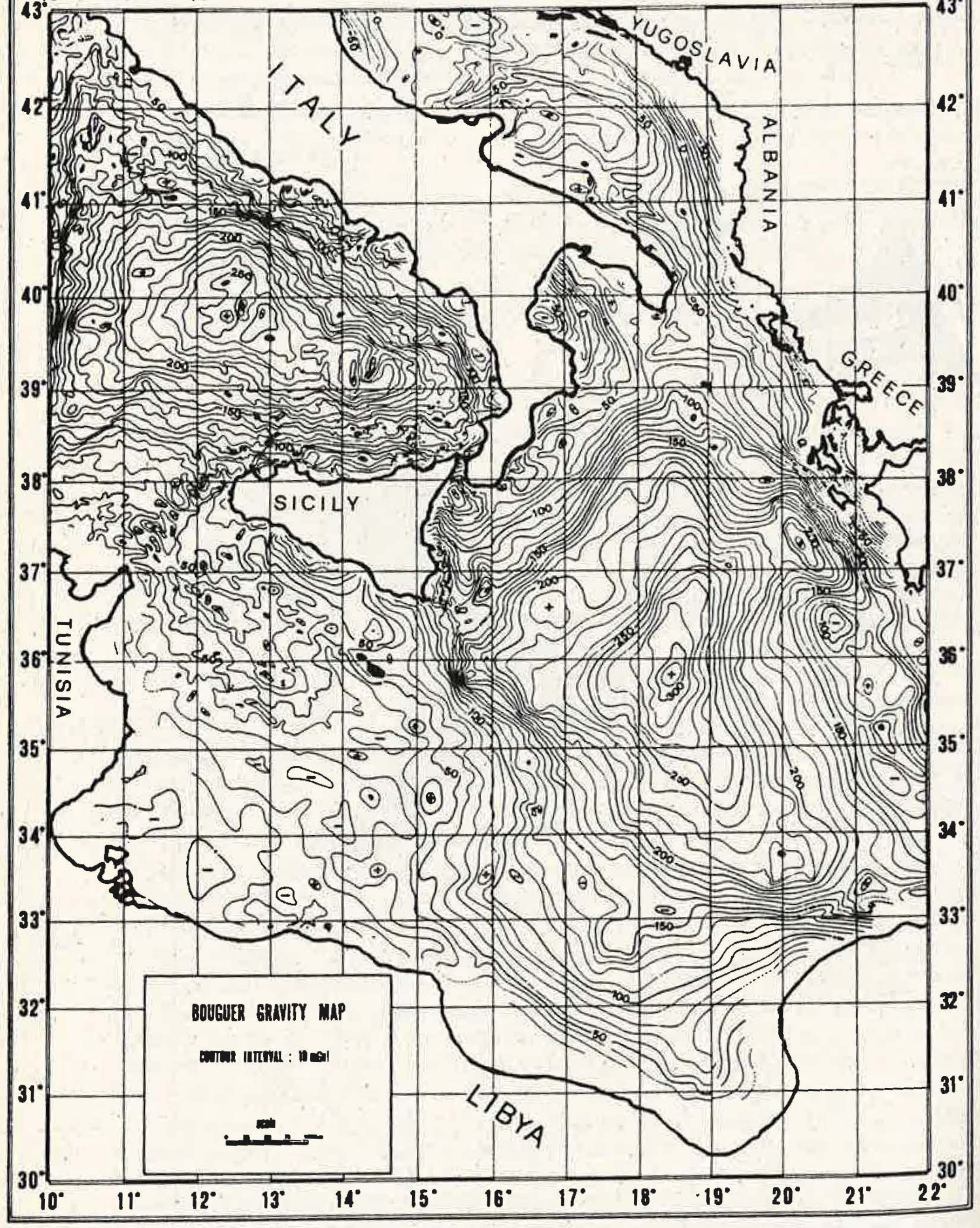


Fig. 2 — *Bouguer Gravity Map of Central Mediterranean.*

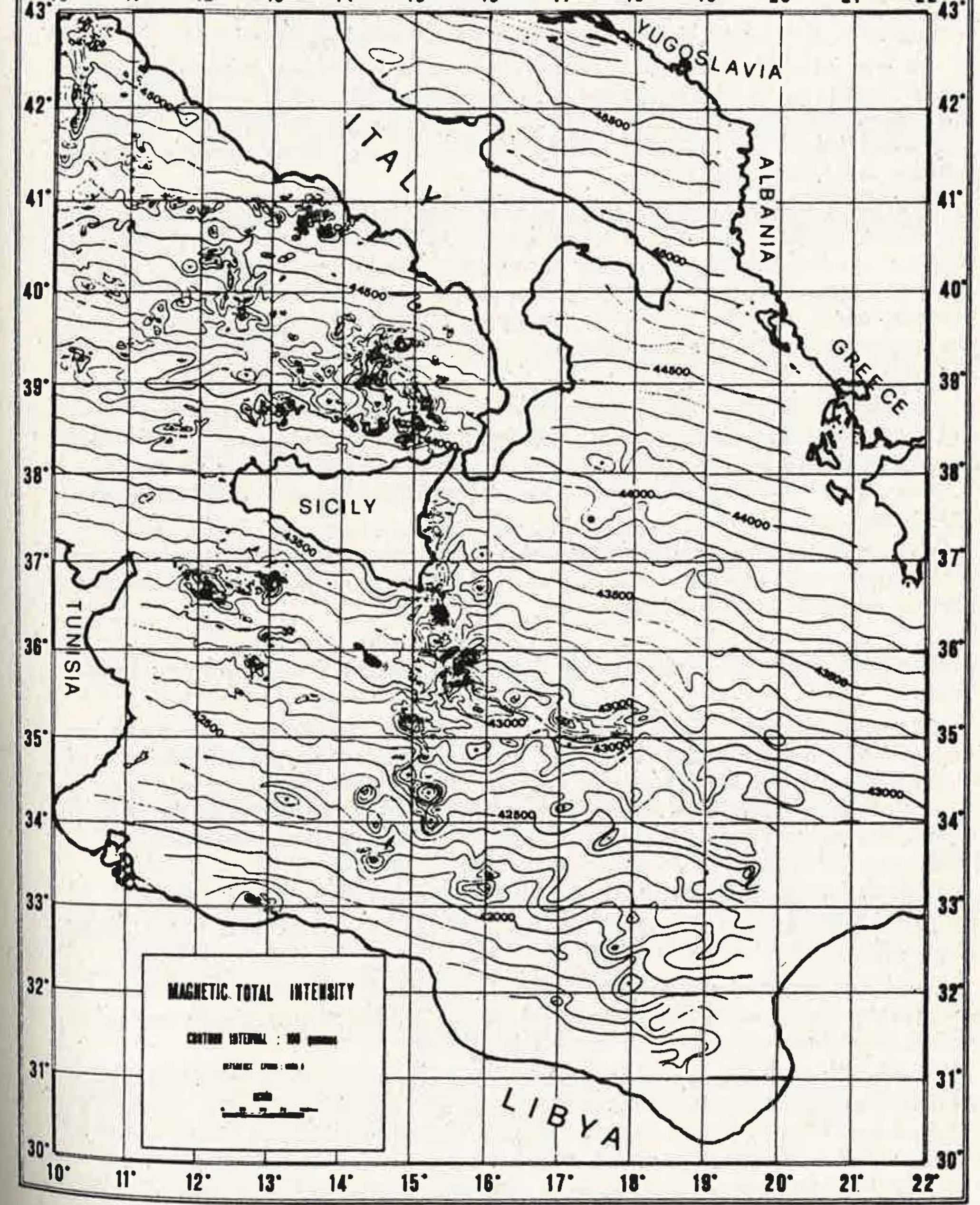


Fig. 3 — *Magnetic Total Intensity Map of Central Mediterranean.*

Antalya-Cyprus Hatay ophyolites and the opening of the Eastern Mediterranean in Mesozoic (Laubscher et al., 1977) is similar in some aspects to that of Biju-Duval et al., (1976).

Based on a deep knowledge of stratigraphic sequences of the Southern Apennines, and assuming several concepts already presented in Laubscher et al., Scandone et al., (1977) propose an interesting geodynamic model of the Central Mediterranean area.

Carey (1976) presents a global geodynamic evolution based on his expanding theory published in 1953. The Author interprets the evolution of Tethys as a consequence of torsional megadeformations, with rotation of blocks.

An original approach to the evolution of the earth's crust and in particular of the Alpine System in the Mediterranean is proposed by Tapponier P. (1977). Following this theory and interpretation, the African promontories of the Italian and Arabian peninsulas played an important role in determining the tectonic conditions in the collision area with stable Europe.

Channel, D'Argenio and Horvath (1979) reconstruct the paleotectonic evolution of the "Adria" plate, considered as a promontory of the African one. The periadriatic orogenic systems are examined and the ideas expressed are supported by several consistent arguments, and new data or data available from careful consultation of the whole literature. Also Semenza (1977), studying in detail the Southern Alps, arrives at the conclusion that the Adriatic (Italo-Austro-Dinaric plate) is substantially a promontory of Africa.

Bosellini (1973) discussed a geodynamic model of the Southern Alps in Jurassic and Cretaceous. Castellarin and Vai (1981) remark on the importance of Hercynian tectonics in the Alpine system. Castellarin, Colacicchi and Praturlon (1978) reconstruct the extensional tectonics along with the important geological area of the Ancona-Anzio line.

Many other important papers have contributed to the progress in the knowledge of the Mediterranean, and only the limit of space does not allow the enumeration of other relevant research works to be continued.

2. Regional structural and stratigraphic conditions of Pelagian and Ionian Seas

All reconstructions of the regional structural and stratigraphic conditions are mainly based on seismic explorations and on remarkable amounts of available data of oil exploration along the continental margins. The most complete regional seismic exploration which covers the whole Mediterranean is that carried out by the OGS of Trieste, and partially published by Finetti and Morelli (1972; 1973) and Finetti (1976, 1981).

Important seismic information on deep water areas of the Mediterranean are given also by the exploration activity of IFP, CNEXO and others: Mauffret et al., (1973); Biju-Duval et al., (1974); Mulder (1973).

These data, together with the drilling results of the JOIDES project (Legs 13 and 42 a) constitute the most useful information for the outline of the existing geological conditions of deep water areas of the Mediterranean.

Particular attention has been dedicated to the Mesozoic extensional geodynamics because of its importance for the reconstruction of the evolution of the area. While of the Pelagian and Western Ionian Sea the tectonics associated with the Mesozoic movements is still evident, in the Eastern Ionian Sea, on the contrary, the successive compressional movements have largely modified the previously existing tectonic setting. Only in a small area between the Calabrian and Hellenic Arcs it is still possible to observe the extended margin of Apulia *(Fig.s 4 & 5)*.

From the stratigraphic and tectonic viewpoint it is possible and convenient to divide the studied areas into seven geological provinces *(Fig. 1)*:

- Pelagian Sea
- Sirte rise
- Ionian abyssal basin
- Apulian platform
- Southern Adriatic basin
- Calabrian arc
- Hellenic arc

These provinces have individual characters which are remarkably different from each other. But in every province its own particular characteristics can be substantially observed over the whole area.

The Pelagian Sea is the most explored province of those studied in this paper, and for its varying characteristics it has been subdivided into seven different geological units *(Fig. 1)*.

2.1 — Pelagian Sea

With this name the area between Sicily, Tunisia (Cape Bon), Tripolitania coast, the upper limit of the Sicily-Malta escarpment and the Medina bank to the east is intended. In literature this part of the Mediterranean is also called the "Strait or Channel of Sicily". We will limit the term "Channel of Sicily" only to the central area of the Pelagian Sea where the prominent rifting process exists and the larger grabens like those of Malta, Pantelleria, Linosa and Medina occur.

To illustrate and describe the varying geological and geophysical aspects of this Sea it is convenient, as above mentioned, to subdivide the area into the following main geological units *(Fig. 1)*:

- Gabes-Tripoli-Misurata basin
- Lampedusa-Medina plateaus
- Sicily Channel rifting area
- Caltanissetta basin
- Ragusa-Malta plateau
- Adventure plateau
- Sicily-Malta-Medina Mounts Escarpment

The last unit (Sicily-Malta-Medina Mounts escarpment) does not belong strictly to the Pelagian Sea. But to follow the relationships between this area and the Ionian abyssal basin, and to examine the remarkable difference between the steep escarpment of Sicily-Malta and that much more gentle of Sirte rise, it is better to give its description immediately after the units previously commented on.

2.1.1 — Gabes-Tripoli-Misurata Basin

This geological unit extends from the Sfax-Gabes area to offshore Misurata. It is limited to the south by the regional extensional fault system of Gafsa-Jeffara, and to the north by the Lampedusa-Medina Plateaus area.

From the tectonic viewpoint this basin is to be considered as the result of old extensional geodynamical movements which occurred in the Triassic and before in the Paleozoic. The two flanks, as well as the trough of the basin are affected by several extensional faults, some of which with remarkable displacements.

Extensional phases, successive to the first ones above mentioned, activated the previously existing faults, and created new ones. After the Paleozoic-Triassic stretching movements other important extensional geodynamic phases occurred in the Middle Jurassic and especially in the Middle-Upper Cretaceous. With this last one are associated remarkable igneous effusions of a basaltic type. Basaltic layers in the Middle-Upper Cretaceous have been found in several points by drilling exploration. These movements were accompanied by a consistent subsidence of the basin. Extensional and subsidence activities occurred also successively. In the Middle-Upper Miocene to Quaternary, one of the main extensional phases which affected not only and not particularly this area took place.

On seismic lines it is possible to identify many more faults than it is possible to indicate on a map on a regional scale like that of *Plates III* and *IV*.

Combining seismic stratigraphy and available borehole data it is possible to reconstruct the following average sequence (thicknesses of Lower Mesozoic in metres by conversion of traveltime following the obtained seismic velocities):

a) Plio-Quaternary (100-350)
b) Messinian interval (0-150)
c) Middle Miocene to Oligocene (1400-2200)
d) Eocene-Paleocene (700-1000)
e) Cretaceous (1200-2000)
f) Jurassic (1500-2600)
g) Permo-Triassic (Probably more than 3000)

Triassic salt walls are known to exist from boreholes made. Seismic evidence of Triassic salt walls, especially on the deeper part of the Gabes-Tripoli basin has been found. From seismic velocity functions it seems clear that Miocene-Oligocene is generally associated with relatively low values (2000 to 3000 m/sec) attributable to predominant shaly-marly sequences. Eocene and Mesozoic are frequently characterized by higher velocities probably corresponding to carbonate intervals, homogeneous and/or inter-bedded with shaly-marly layers.

2.1.2 — Lampedusa-Medina Plateaus

Along with the median area of the Pelagian Sea there exist two regional structural highs: that of Lampedusa and that of Melita-Medina banks. Even if these structures show several local variations with very gently ondulations and many young normal faults with horst and grabens, schematically we can consider them, in a regional manner, as two large plateaus. Such features are limited to the south by the Gabes-Tripoli-Misurata basin, and to the north by the troughs of Linosa and Medina Grabens *Plate III*. While the Lampedusa Plateau is regionally an unique high, the Melita-Medina plateau is much more fragmented and constituted by different highs and lows affected by numerous faults.

The Lampedusa plateau is higher than the Melita-Medina one. To compare the height of the two structures the Lampedusa area has been assumed as that inside the isochrone of 1.0 sec, while the Medina Bank area has been assumed as that inside the isochrone of 1.6 sec (top Mesozoic, *Plate III*). So Lampedusa plateau on average results about 0.6 sec, or about 0.9 km higher.

Examining the geological evolution of these parts of the Pelagian Sea, it seems possible to say that the Lampedusa-Medina plateau is a regional high area that has existed for a long time: at least since the Cretaceous. The more recent movements of the Miocene-Quaternary extensional phase produced fracturation with creation of local uplifted blocks and grabens within the regional swell.

Both the Lampedusa plateau and the Melita-Medina plateau areas are affected by more or less consistent volcanic activities. The Medina Bank especially shows several prominent magnetic anomalies. Probably the Cretaceous phase is the most consistent and widely diffused one. But also the last extensional phase (Miocene to Quaternary) seems to have locally affected the area along with the major faults.

By interpolation and extrapolation on seismic lines of the conditions known in the Gabes-Tripoli-Misurata basin and on the Sicily-Malta plateau it is possible to predict the following average stratigraphic condition for the Lampedusa and Medina Bank areas (thickness in metres):

1) *Lampedusa plateau area*
a) Plio-Quaternary (0-350)
b) Messinian (0-50)
c) Middle Miocene to Oligocene (1200-1500)
d) Eocene-Paleocene (500-900)
e) Cretaceous (2200-3000)
f) Jurassic (1200-2200)
g) Permo-Triassic (More than 2000)

2) *Medina bank area*
a) Plio-Quaternary (0-250)
b) Messinian (0-50)
c) Middle Miocene to Oligocene (200-900)
d) Eocene-Paleocene (200-900)
e) Cretaceous (3000-5000)
f) Jurassic (2400-3000)
g) Permo-Triassic (More than 2000)

At the Lampedusa Island a Cainozoic-Mesozoic limestone sequence is outcropping and the structural uplift is limited to the north by a remarkable fault. The predominant trend is that parallel to the axis of the Pelagian Sea: NW-SE. At the Medina bank area the Tertiary sequence is generally thicker than on the Lampedusa Plateau. Mesozoic, following our seismic interpretation, seems substantially comparable in terms of thickness in the two considered plateaus.

2.1.3 — Sicily Channel Ritfing Area

The morphological setting of the Pelagian Sea, for the most part, is relatively young and associated with geotectonic conditions.

The regional structural conditions can be assumed as substantially tabular on the fractured parts of the basin and everywhere before the "NQ" rifting phase. During the last main extensional phase of the Miocene-Quaternary a remarkable stretching and faulting activity affected the whole Pelagian Sea and in particular the area of the Sicily Channel in correspondence with the major grabens of Pantelleria, Linosa, Malta and Medina (*Plate III*). Before this geodynamical phase, a long period of relatively not important movements or quiet conditions occurred in the Pelagian Sea. During this interval of time the whole Pelagian Sea area was a basin where sedimentation took place with continuity on a sea bottom having moderate depth variations from place to place, with few limited exceptions, like for example the areas of Lampedusa and Lampione Islands. Malta Island, from the whole Middle Miocene back in time to at least the Cretaceous, did not exist.

The Middle-Miocene-Quaternary stretching and rifting activity produced here the most widely distributed deformation process with numerous normal faults, some having remarkable displacements *(Fig.s 11, 12, 13)*. During this geodynamic activity the Pelagian sea assumed the present sea-bottom setting with the generation of major grabens like those of Malta, Pantelleria, Linosa, and Medina *(Fig. 9)*. In the Upper Miocene-Early Pliocene, or about 10 m.y. ago, the block of the Maltese Islands emerged. Examining in detail the structural setting and evolution of the Malta graben and Maltese Islands it is possible to make some important remarks:
a) Maltese Islands block is structurally a Horst *(Fig. 11)*.
b) The extensional and rifting movements of major grabens as well as that of Malta, are generally accompanied by tilting processes of the two uplifted blocks on both sides of the considered graben. Maltese Islands are generated by the tilting of the NE block of the Malta Graben.

Rifting movements of this "NQ" phase are also associated with a prominent volcanic activity which occurred in several parts of the Sicily Channel. The most important outcropping volcanic shows are those of the Pantelleria and Linosa Islands. But exploration activity and magnetic anomalies indicate that several other areas were affected by volcanism from the Miocene to the Quaternary. See for example Medina Graben *(Fig. 9)*.

The stratigraphy of this area, following seismics, shows appreciable variations in terms of thickness and probably also of lithology. In fact it is possible to see horizontal seismic velocity changes along with equivalent time-stratigraphic intervals. In the following list the time stratigraphic intervals of the Malta area resulting from seismic exploration are given:

a) Marine Plio-Quaternary and Messinian (Missing)
b) Miocene to Oligocene (500-600)
c) Eocene-Paleocene (700-1000)
d) Cretaceous (1200-1500)
e) Jurassic (1800-2200)
f) Permo-Triassic (More than 3000)

Here, as well as on the whole area from Ragusa to Medina Mounts, the Middle Jurassic is affected by the most impressive volcanic activity (Phase "J"). More modest volcanic shows occur also in the Cretaceous extensional phase ("K"). The entire Mesozoic sequence of the Malta area furnishes high seismic velocities, in accordance with the existence of a carbonate sequence which is here much more continuous than in the Ragusa and the Medina bank areas.

2.1.4 — Caltanissetta Basin

Central Sicily is geologically characterized by a very thick Neogene basin known as "Caltanissetta Basin". The thickest stratigraphic sequence is that of Miocene (2000 to 4000 m) which terminates with the late Miocene evaporitic interval. This evaporitic succession in the Caltanissetta basin is constituted by evaporitic and terrigenous sediments cyclically alternated. Evaporitic deposits here are so typical that from the town of Messina, this chronological interval (Messinian) takes its name.

Since the Early Neogene the basin has been affected by a marked subsidence accompanied by high rate deposition. From the Middle Miocene to the Quaternary, both the gravitative sliding and the compressional geodynamics determined an exasperate tectonics with shearing planes, overthrusts and chaotic allochtonous conditions.

Movements continued also during the Quaternary as the existence of the Quater-

nary olistostrome in South Sicily and the Gulf of Gela *(Plate III)*, indicates.

This basin extends in the Pelagian Sea towards SE in the area north of Malta. Stratigraphically, the area between Malta and Ragusa, from the Eocene to the Mesozoic is similar to that of Malta. But here also the Oligocene and a thicker Miocene, and thin Plio-Quaternary exist. More detailed stratigraphical and structural conditions are reported in Patacca et al., (1981).

2.1.5 — Ragusa-Malta Plateau

The area between Ragusa and Malta, limited to the East by the Sicily-Malta escarpment, is constituted by a very thick Mesozoic sequence covered by a Cainozoic progressively thinning from west to east and from south to north. In south-east Sicily, and near the limit of the escarpment, the Mesozoic outcrops, or is very shallow. The whole Ragusa-Malta area shows gentle ondulation mostly trending NE-SW in the northern part. But also NW-SE less pronounced trends can be identified. Faults are not so numerous as in the area of the major grabens (Malta, Pantelleria, Linosa ad Medina grabens) and are in gereral older because they are frequently associated with the Mesozoic extensional phases ("J", "K"). In some cases the paleo-fault systems stopped their activity during the first generating extensional phase; in some others they were renewed by successive phases. Regionally, the Ragusa-Malta platform area can be considered as an asymmetric ridge trending N-S and affected by clear and remarkable tilting movements near the Sicily-Malta escarpment. Such tilting is associated with the main extensional phase which is here that of the Middle Jurassic ("J"). But also the Cretaceous ("K") and Neogene-Quaternary phase ("NQ") continued the uplifting and tilting movements of the block.

The Maltese Islands are constituted by small emerging areas of the uplifted block which limits to the North the Malta graben. Uplifting of this block and the emersion of the Maltese Islands are due to the tilting movements which is associated with the "NQ" rifting of the Sicily Channel area. The Maltese Islands block structurally is a horst '*Fig. 11)* from which the Islands emerged about 10 m.y. ago, at the end of Miocene.

The whole Ragusa-Malta platform area is affected by prominent volcanic activities which occurred at different regional stretching phases. Four main phases *(Fig. 32)* can be identified: Middle-Upper Triassic ("T"), Middle Jurassic ("J"), Upper Cretacecus ("K") and Neogene-Quaternary ("NQ").

In this area, all the phases produced intense activities with thick to very thick volcanic intervals. Particularly impressive is the Middle Jurassic phase. In fact, the relative interval is almost completely constituted by igneous rocks. But also the Middle-Upper Triassic (Patacca et al., 1981) shows a remarkable volcanic activity with many basaltic intervals in "Streppenosa" formation (Black Shale).

2.1.6 — Adventure Plateau

The area offshore of SW Sicily, known as "Adventure Plateau" is substantially flat at the sea bottom surface, but shows remarkable geodynamic movements and tectonization in subsurface. Both extensional and compressional movements, with predominance of the first one, affected the area. Extensional deformation and associated normal faulting is predominantly trending parallely to the Sicily Channel (WNW-ESE). Compressional effects and reverse faulting, generally parallel to the Maghrebian trend (NE-SE), are much more modest than the extensional ones.

From SW Sicily toward Pantelleria Island the reflecting sequence shows a general progressive thickening of Mesozoic and Lower Tertiary. The Middle-Upper Miocene is characterized by a prograding sequence overlying a relatively thin Lower Miocene. Generally Jurassic is thin to very thin or missing.

Average time-stratigraphic sequence can be summarized as follows (thickness in metres):

a) Plio-Quaternary (0-1000)
b) Messinian (0-200)
c) Middle-Upper Pre-Messinian Miocene (200-2000)
d) Lower Miocene (0-800)
e) Eocene-Oligocene-Paleocene (200-800)
f) Cretaceous (600-1400)
g) Jurassic (0-500)
h) Triassic (> 3500)

The "NQ" extensional phase produced the most remarkable deformations with several volcanic shows, especially in the Southern part of the plateau.

2.1.7 — Sicily-Malta-Medina Mounts Escarpment

A very important geological meaning is assumed by the Sicily-Malta escarpment. Tectonically, it is affected by a normal regional mega-fault system that diminishes its total displacement from Sicily *(Fig. 6)* to the Medina Mounts *(Fig. 7)* about 1.5 second, two-way time, at Middle Jurassic layers.

South of the Ragusa Plateau *(Fig. 6)* there exists a complete thick Mesozoic, covered by a thin Eocene (about 200 m). Then a very big extensional fault system brings to the down block of the Ionian abyssal area with a slope directly constituted by the fault plane. It is evident, even from seismic characters, that up-block and down-block have very different Tertiary sequences: very thin and only of Eocene age the Upper block, and very thick and with a much more complete sequence the down one. Stratigraphy and tectonics of the down block are very indicative of the involved geodynamics. In fact it is possible to remark that the fault system commenced its activity in the Mesozoic and continued in the Tertiary. In particular during the Miocene a prominent foundering of the Ionian Sea as a consequence of the "NQ" extensional phase occurred.

The most important and significant difference between the up and down block of this ara is not in the Tertiary, but very probably, in the Mesozoic and in the Crustal characters. After several years of geophysical, geological, and drilling exploration activities, studying all obtained data, the Author has arrived at the conclusion that the Ionian abyssal basin is constituted by a paleo-oceanic crust open during the Mesozoic. Arguments in support of such an interpretation are discussed later on in paragraph 2.3.

Structurally, the Medina Mounts are constituted by a complex fractured horsts system tranding W-E in the western part *(Fig. 37)*. Associated prominent magnetic anomalies *(Fig. 3)* in addition to seismic information *(Fig. 7)* indicate that this feature is affected by volcanism.

Examining more carefully the seismic exploration results it is possible to remark and/or deduce the following:

a) The northern flank correlates very well, in terms of existing extensional faults and age of generating geodynamics with the Sicily-Malta escarpment. All geophysical data indicate that the northern escarpment of the Medina Mounts is the continuation of the Sicily Malta escarpment. In the Medina Mounts the total displacement of the invovled extensional fault system is smaller than in the Sicily-Malta escarpment.
b) The blocks forming the feature are differently foundered with respect to the Malta-Medina shallow platform area up to a depth of more than 2000 metres *(Fig. 7)*. The foundering process of these blocks, very probably, commenced during the Cretaceous extensional phase ("K") where the whole Sirte Rise was greatly stretched. But the geodynamic phase that contributed the most is evidently that of

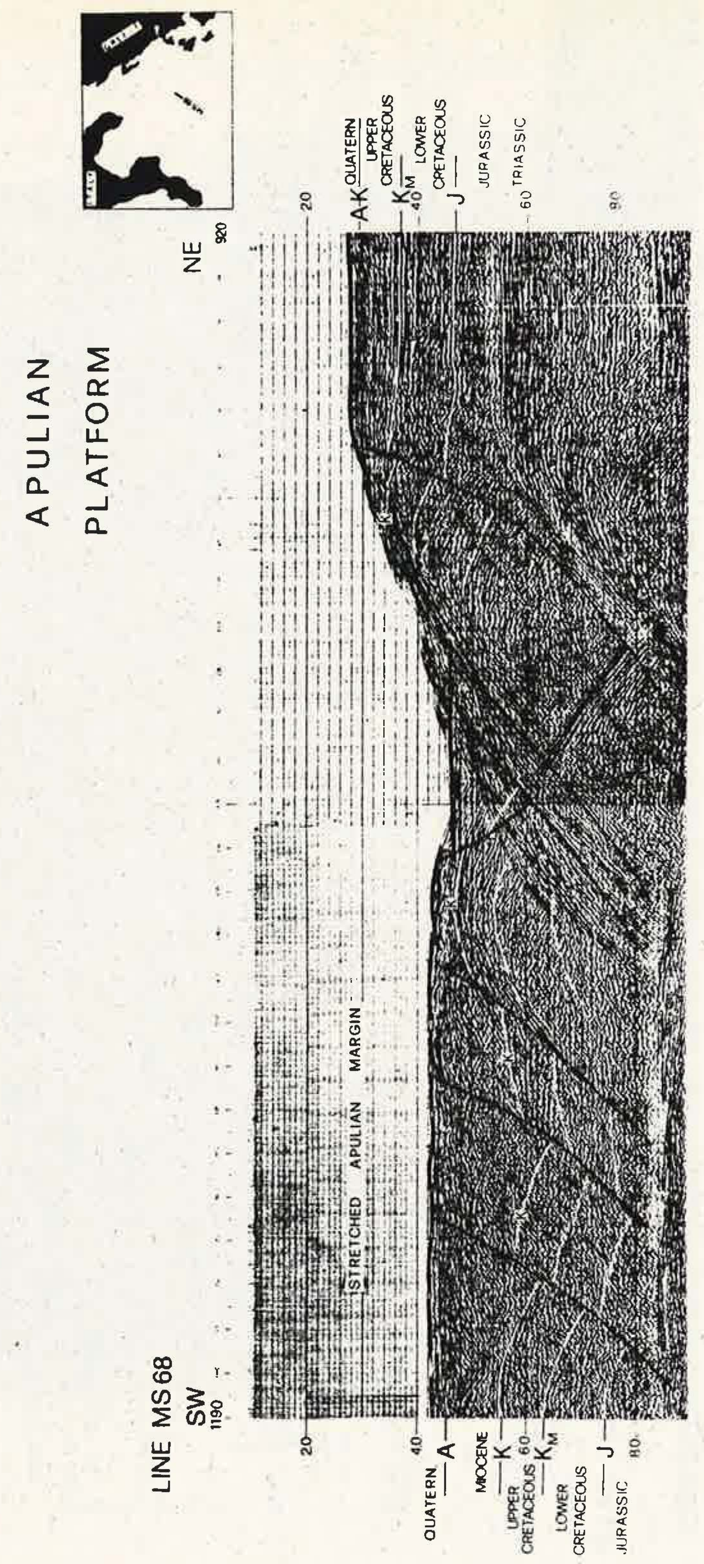


Fig. 4 — Example of Interpreted Seismic Reflection Line on Ionian Margin of Apulian Plate (Line MS-68; S.P. 1190-920).
Evidence of extensional geodynamics with fragmentation and tilting.

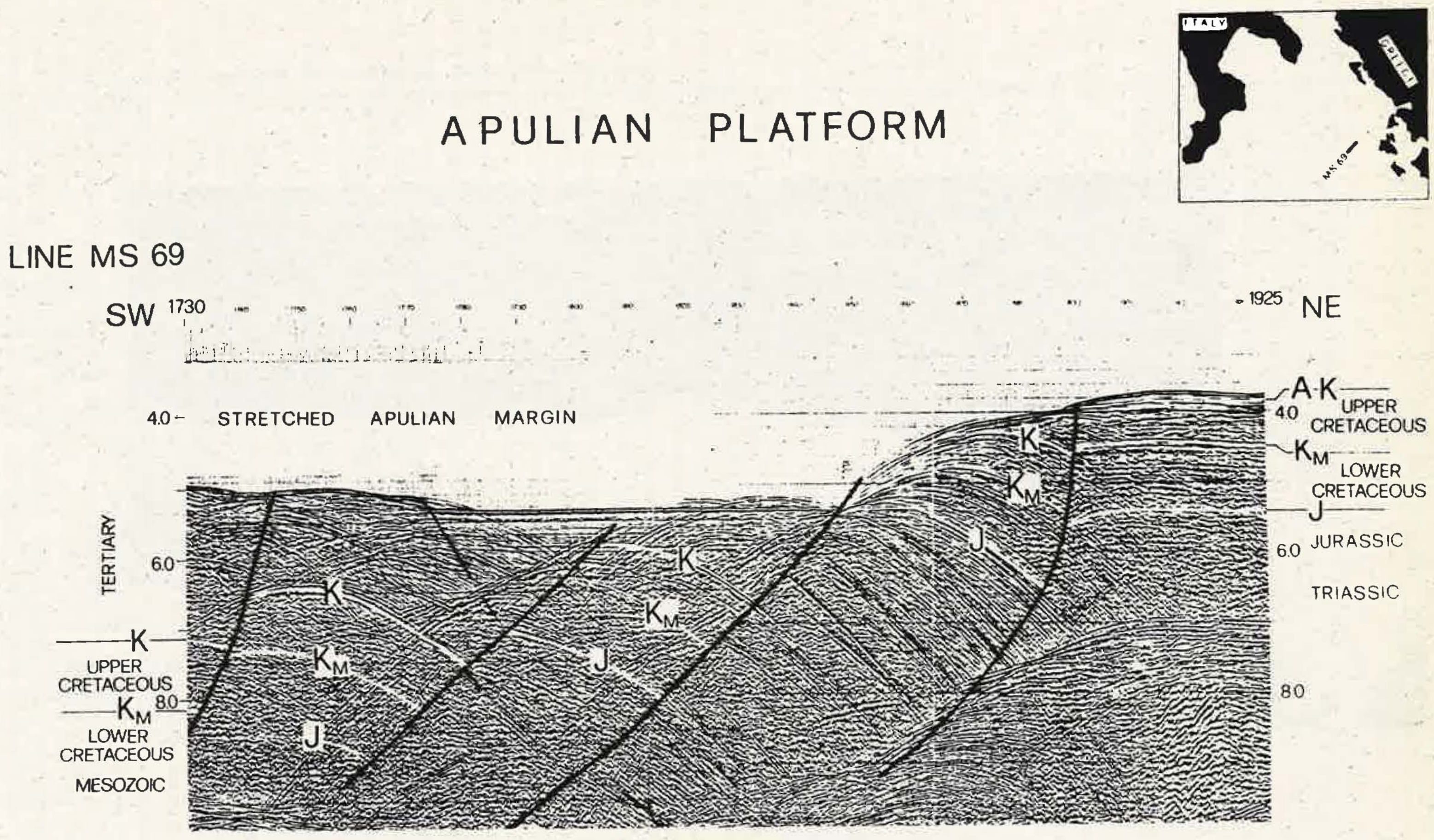


Fig. 5 — *Example of Interpreted Seismic Reflection Line on Ionian Margin of Apulian Plate (Line MS-69; S.P. 1730-1925).*
It shows the same geodynamical process of *Figure 4.*

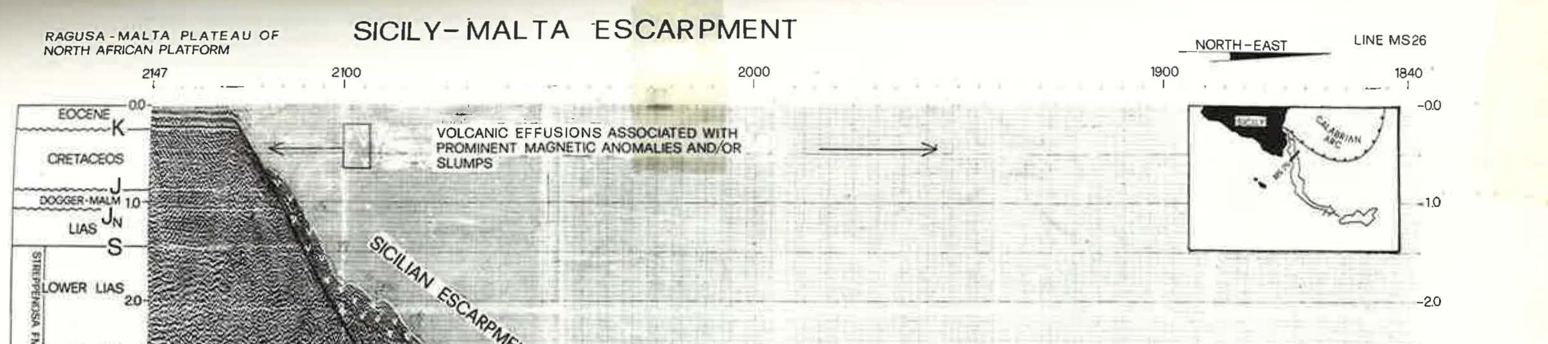


Fig. 6 — *Example of Interpreted Seismic Reflection Line on Sicily-Malta Escarpment (Line MS-26; S.P. 2147-1840).*
It shows the passage from Ragusa-Malta Plateau area to the Ionian conditions. Evidence of old extensional geodynamics, with mega-fault system and crustal opening.

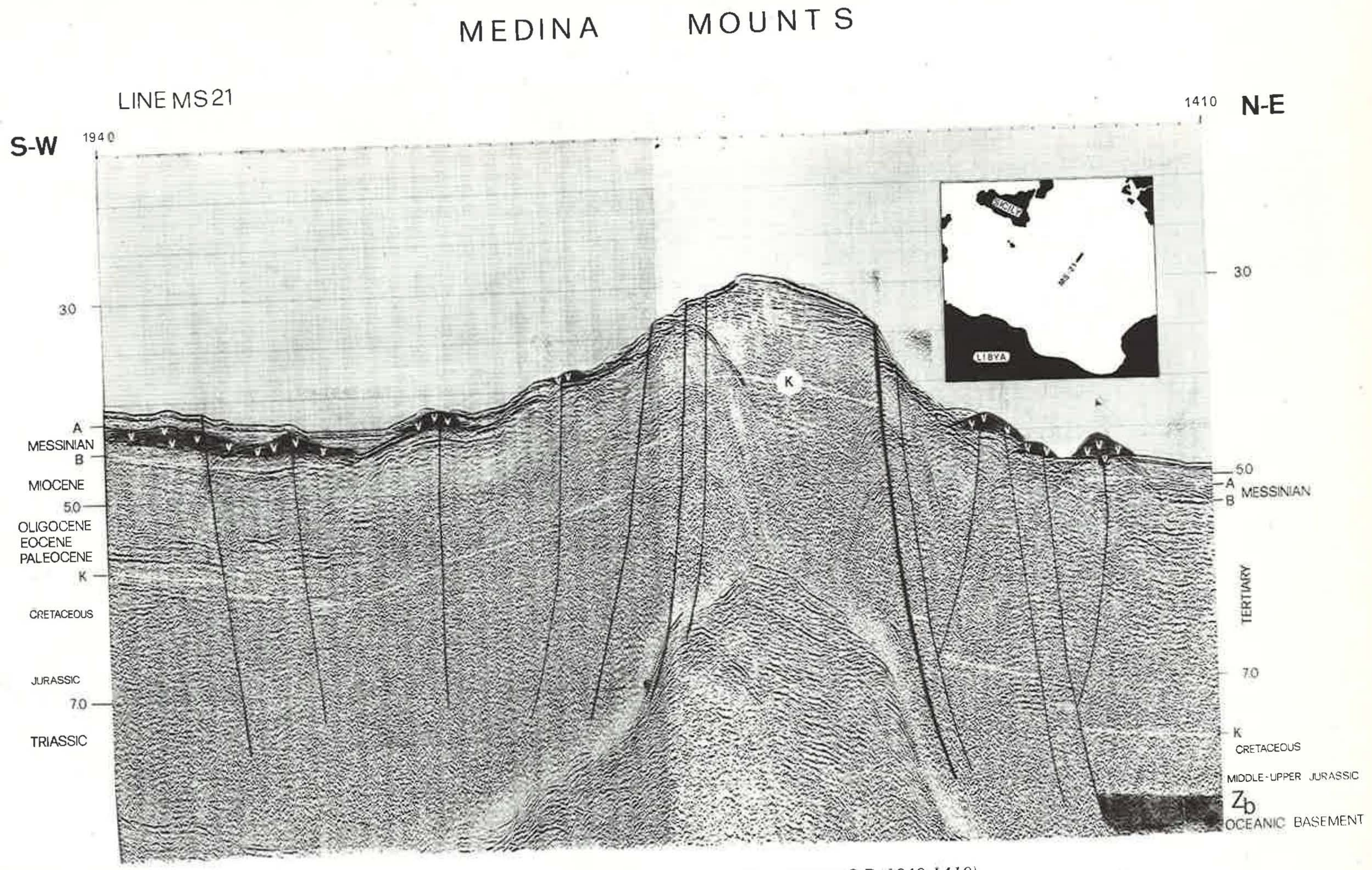


Fig. 7 — *Example of Interpreted Seismic Reflection Line Across Medina Mounts Area (Line MS-21; S.P. 1940-1410).*
The Mega-Fault System between Medina Mounts and the Ionian Basin is the continuation of the Sicily-Malta Escarpment seen in *Figure 6*. Evidence of young volcanic activity associated with the "NQ" extensional phase.

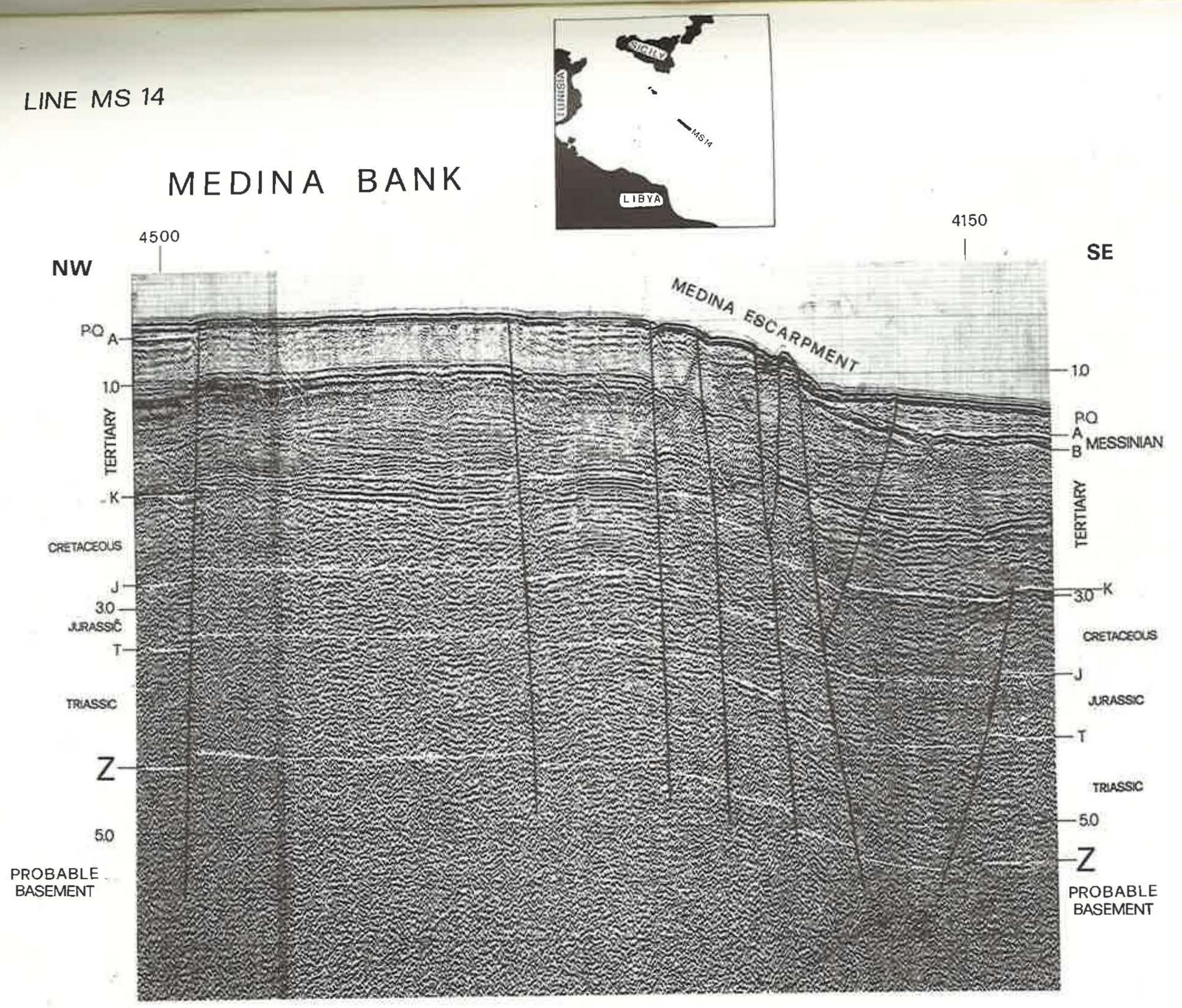


Fig. 8 — *Example of Interpreted Seismic Reflection Line On Medina Bank and Medina Escarpment Area (Line MS-14; S.P. 4510-4110).*
It shows the continuity of the Mesozoic-Tertiary African Plate Sequence, not affected by faults in Medina Bank area. The extensional faults of Medina Escarpment were produced during the "K" and "NQ" stretching phase.

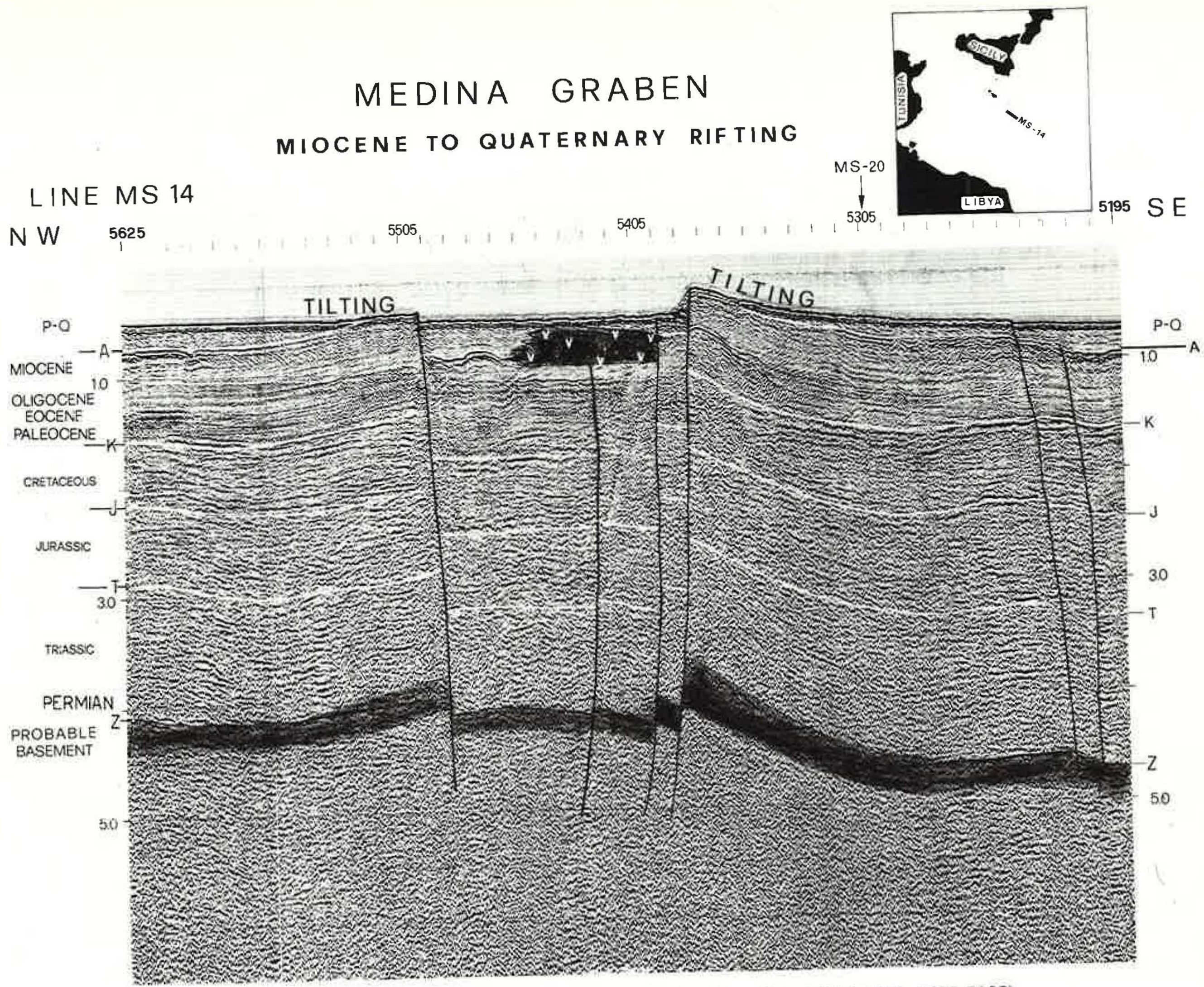


Fig. 9 — *Example of Interpreted Seismic Reflection Line Across Medina Graben Area (Line MS-14; S.P. 5625-5195).* Medina Graben in created during the "NQ" extensional geodynamics, as well as all major grabens of Central Pelagian Sea. Evidence of young volcanic activity (Plio-Quaternary) associated with prominent magnetic anomaly. Remarkable tilting process involving also deep layers and very probably lower crust.

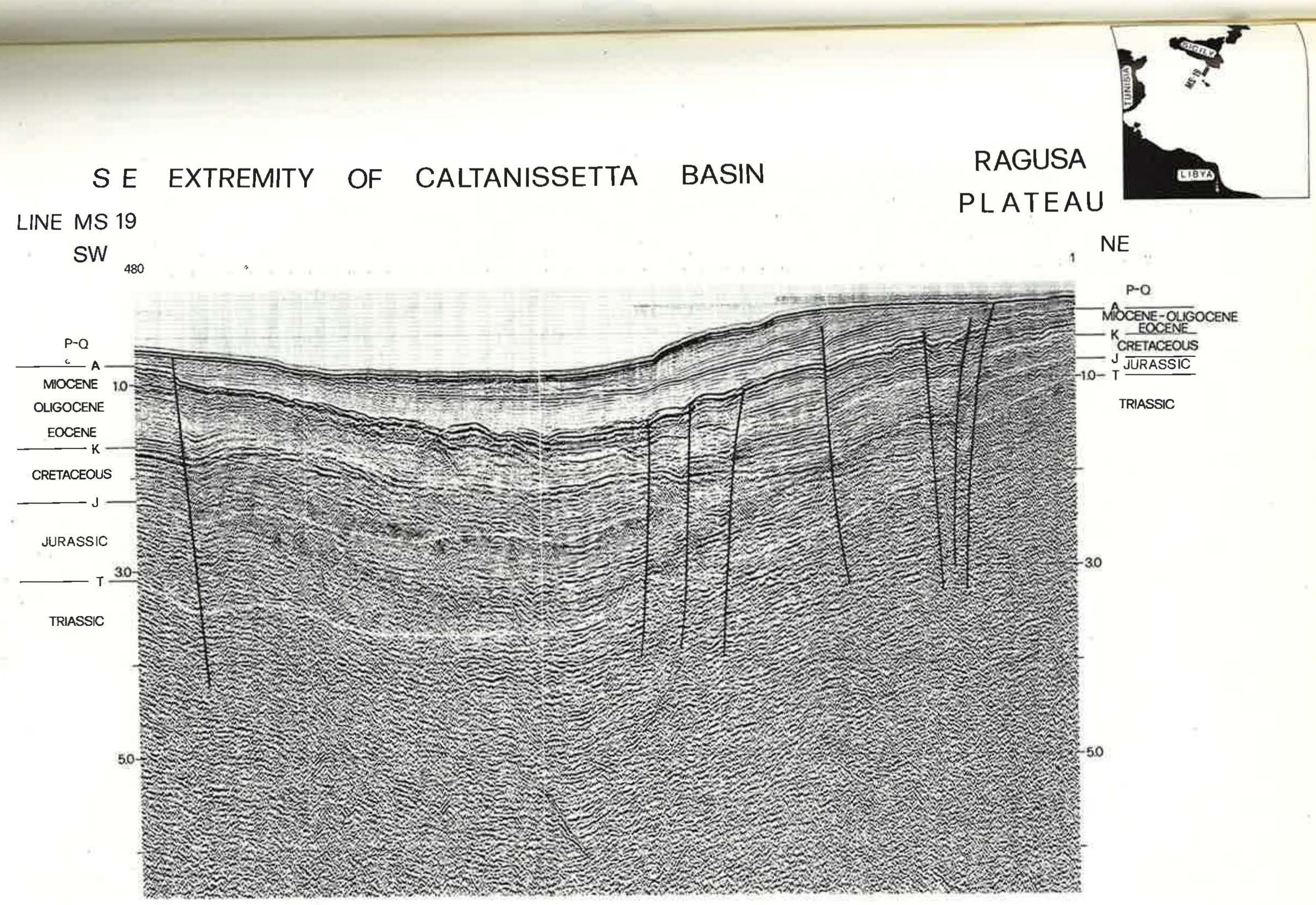


Fig. 10 — *Example of Interpreted Seismic Reflection Line Across the South-East Extremity of Caltanissetta Basin (Line MS-19; S.P. 480-1).*

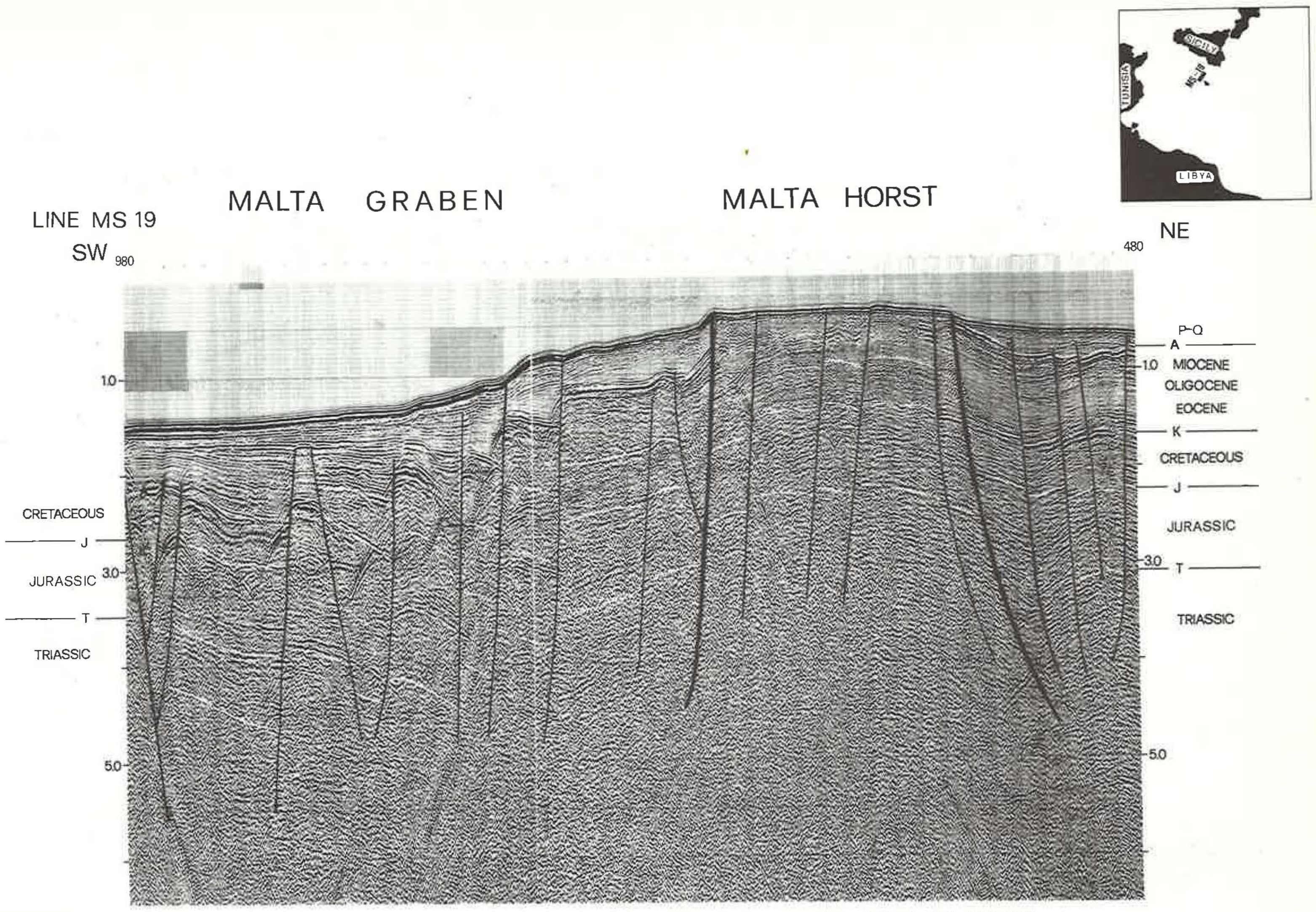


Fig. 11 — *Example of Interpreted Seismic Reflection Line Across Malta Horst and Malta Graben Area (Line MS-19; S.P. 980-480).*
It is the continuation of previous Figure, and the four Figures 10, 11, 12 and 13 show the entire line MS-19. In this Figure 11 it is evident that the structure of Malta corresponds to a horst. Malta Graben is affected by a prominent rifting process occurred in "NQ" extensional phase.

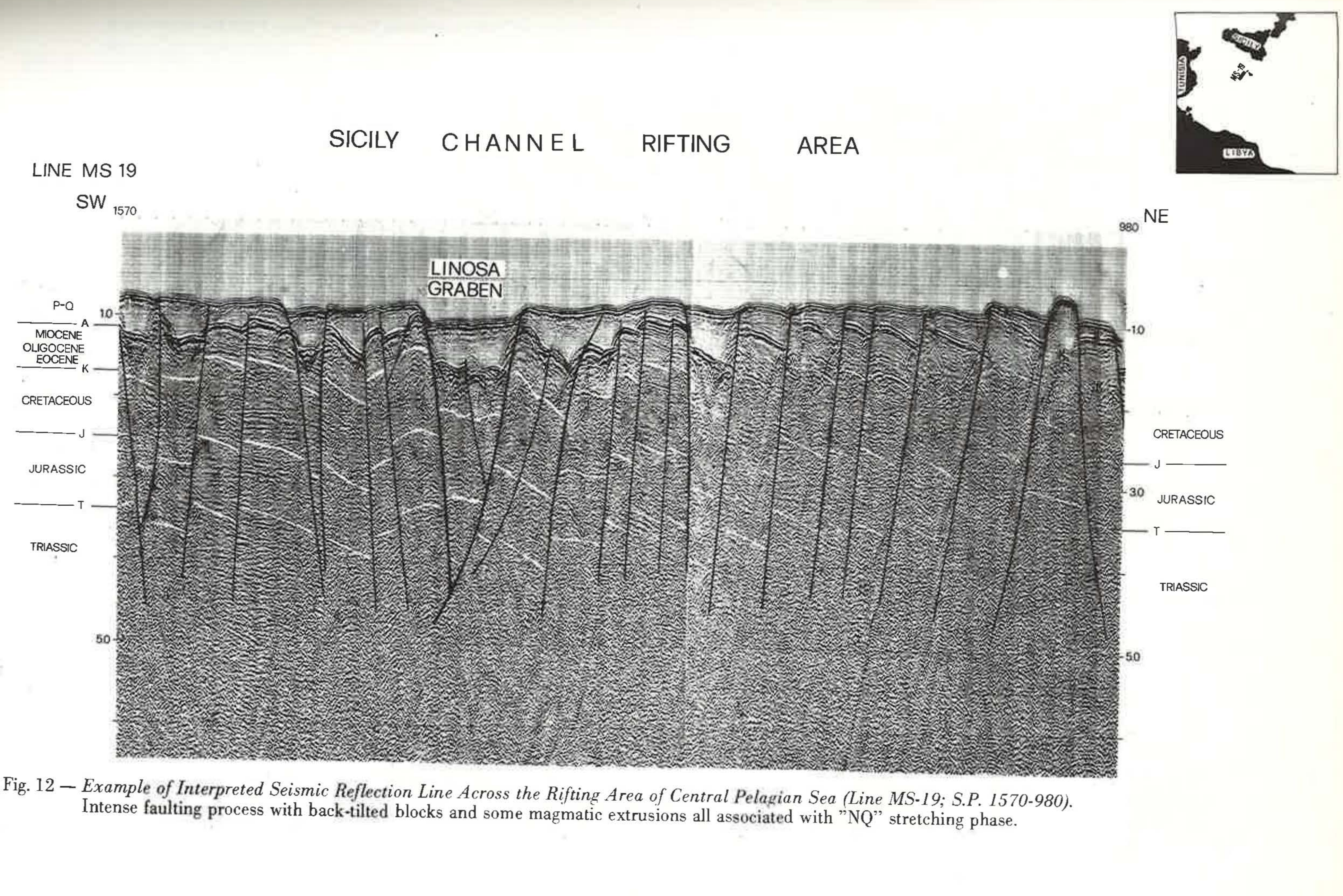


Fig. 12 — *Example of Interpreted Seismic Reflection Line Across the Rifting Area of Central Pelagian Sea (Line MS-19; S.P. 1570-980).*
Intense faulting process with back-tilted blocks and some magmatic extrusions all associated with "NQ" stretching phase.

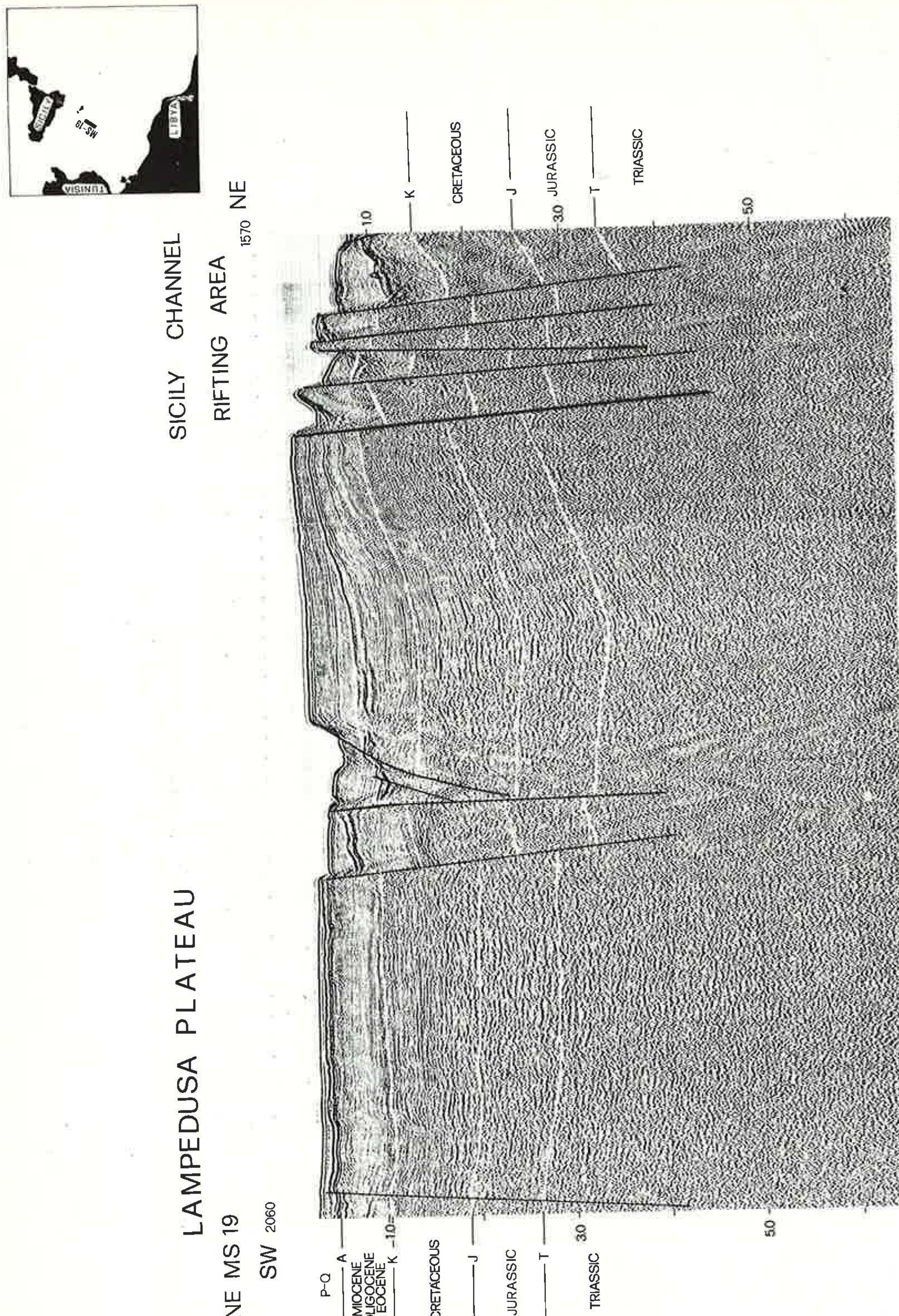


Fig. 13 — *Example of Interpreted Seismic Reflection Line Across the Rifting Area of Central Pelagian Sea and the Tabular Area of Lampedusa Plateau (Line MS-19; S.P. 2060-1570).*
It shows the end of the rifted area and the much more quiet conditions of the Lampedusa Plateau.

the Miocene-Quaternary ("NQ"). On the contrary during the crustal opening phase "J", this area was very probably uplifted by tilting movements.

c) The Mesozoic blocks of the Medina Mounts are covered by different thichnesses of Tertiary from relatively thin to very thin. In some cases the Mesozoic outcrops.
d) The southern flank of the Medina Mounts is determined by extensional faults having in general a much more modest displacement *(Fig. 7)*. The faults very probably commenced in the Middle-Upper Cretaceous (phase "K"), during the generalized stretching activity which affected the Sirte Rise. During the Miocene-Quaternary extensional phase, all the major existing fractures were newly activated and the displacements of the faults of the southern flank of the Medina Mounts are mostly due to these last geodynamical movements.

2.2 — Sirte Rise

With this term the whole Sirte margin area between the Sirte coast, the east limit of the Medina and Melita plateau and the Ionian abyssal basin is identified *(Fig. 1 & Plate III)*.

The regional structure of this geological province can be schematically considered as a monocline affected by numerous extensional faults accompanied by tilted blocks. Assembling numerous exploration data, and extending the calibrated or reconstructed stratigraphic and structural information to the deep water of the Sirte Rise, it is possible to summarize the following remarks:

a) In the area of the Gulf of Sirte, as is well known, on a Cambro-Ordovician or Hercynian basement, marine sedimentation commences in the Upper Cretaceous and continues until the Quaternary.
b) Off the upper slope *(Plate III)* from about the isochrone 3.0 to 3.6 sec area, below the calibrated Upper Cretaceous sediments, a reflecting sequence, that can be correlated with the Lower Cretaceous to Triassic sequence known in the surrounding Pelagian Sea and Cyrenaica areas onlaps and progressively thickens seaward. Anyhow, this pre-Upper Cretaceous reflecting sequence in the Sirte Rise seems relatively thin.
c) Both the seismic data and calculated magnetic basement indicate that in the Sirte trough the thickest and more complete sedimentary sequence of the Sirte Rise exists. The magnetic basement is expected here at about 7 to 8 km, including 1.8 km of water. From the Paleozoic to the Lower Jurassic a maximum total thickness of about 2.3 km has been calculated. Then, the Middle-Upper Jurassic to Oligocene sequence is generally thin (maximum 1.8 km in Sirte trough. The Miocene thickens progressively seaward and in the Ionian abyssal basin arrives at more than 3 km. The maximum Messinian thickness is about 1 km. The Plio-Quaternary is thin everywhere (100-400 m).
d) The fault pattern of the Sirte Rise suggests that initial extensional movements commenced probably in the Middle Jurassic during the crustal opening of the Ionian Sea. But the main stretching phase and subsidence occurred in the Middle-Upper Cretaceous, when the prominent marine ingression of the Sirte basin took place. Also the "NQ" phase was active as indicates the fact that several faults affect the Tertiary Quaternary layers.
e) From the Cyrenaica ridge to the Ionian abyssal basin, or from about 6.0 to 7.0 seconds on the top Mesozoic time structural map *(Plate III)*, crustal conditions that can be attributed to an "intermediate type" exist.
It is probably here that the SE continuation of the paleo-tectonic area, corresponding to the Sicily-Malta-Medina mounts escarpment, stretched during the "J" phase, and successively enourmously modified by the younger extending processes, is to be found.

2.3 — Ionian Abyssal Basin

For several years, many investigations have been conducted in the Ionian Sea with the purpose of understanding the geological conditions and geodynamical evolution of such a key area of the Mediterranean.

In the past, when geophysical information was morescarce, thecrustal conditions of the Ionian were strongly questioned. Successively, various Authors favoured the hypothesis that the Ionian basin (abyssal plain) is an old oceanic crust covered by a thick sedimentary sequence. But still continental crusts are supported by some Authors.

In the present scientific paper, the Author, after examination and interpretation of a great amount of geophysical geological and borehole data, summarizes his view.

Various data, interpretative elements, and arguments support the idea that the Ionian abyssal basin area is composed by a paleo-oceanic crust. Moreover, the interpretation of a regional seismic exploration covering the entire Mediterranean, and the numerous borehole data and seismic evidence on the occurred volcanic activities, indicate that crustal opening very probably took place during the Middle Jurassic.

To summarize, it is possible to list the following arguments in support of the existence of a paleo-oceanic crust in the Ionian abyssal basin:

a) From the calibrated area of the Sirte basin and the Southern Pelagian Sea, seismic explorations allow some continuous clear reflectors to be followed up to the Ionian abyssal basin with high reliability regarding horizon identification. These reflectors indicate that the base of the Upper Cretacecus-Mesozoic sequence, which onlaps the basement and is fully calibrated in the Sirte basin, continues up to the Ionian abyssal basin with thinner sequences.

b) On the Sirte slope, the Upper Cretaceous is underlain by older sediments having angular unconformity. These sediments thicken in the Sirte trough and again become relatively thin from the Cyrenaica ridge to the abyssal basin, along with the Lower Sirte slope.

c) The acoustic basement is strongly fractured, not clear from the Sirte basin to the Cyrenaica ridge, and on the upper part of the area between the ridge and the abyssal basin. Then the basement becomes flat, more clear, and continuous except when recent volcanoes occur. This last basement seems more similar in character to that of an oceanic crust.

d) From the calibrated area of SW Melita plateau, seismic reflectors, picked up to the Sirte rise ad the Ionian abyssal basin, indicate that in the Sirte rise, under the Upper Cretaceous base (unconformity) older sediments attributable to a time-interval from Lower Cretaceous to Triassic exist. These sediments are thinning in the Sirte rise due to evident stretching and rifting processes which occurred during the "K" phase and probably also the "J" phase.

e) The reflectors calibrated in the Sirte basin and in the Melita plateau area, and picked up to the abyssal basin, correlated across the Sicily-Malta escarpment, with the chronologically equivalent reflectors calibrated in the Sicily-Malta plateau area, indicate that, very probably, the lower part of the Mesozoic sequence is missing in the Ionian block.

f) The studied area shows that the Middle Jurassic, everywhere on the Ragusa-Malta plateau, up to the Medina mounts, is affected by prominent volcanic activity constituted by widely diffused basaltic extrusions.
Igneous rocks intervals are impressively continuous both in time and space on the greater part of the Middle Jurassic of the Sicily-Malta area, near the escarpment. Such activity is surely associated with a mega-geodynamic event that cannot be, logically, explained by a simple continental rifting process.

g) The Bouguer gravity map shows that in the Ionian abyssal basin the absolute

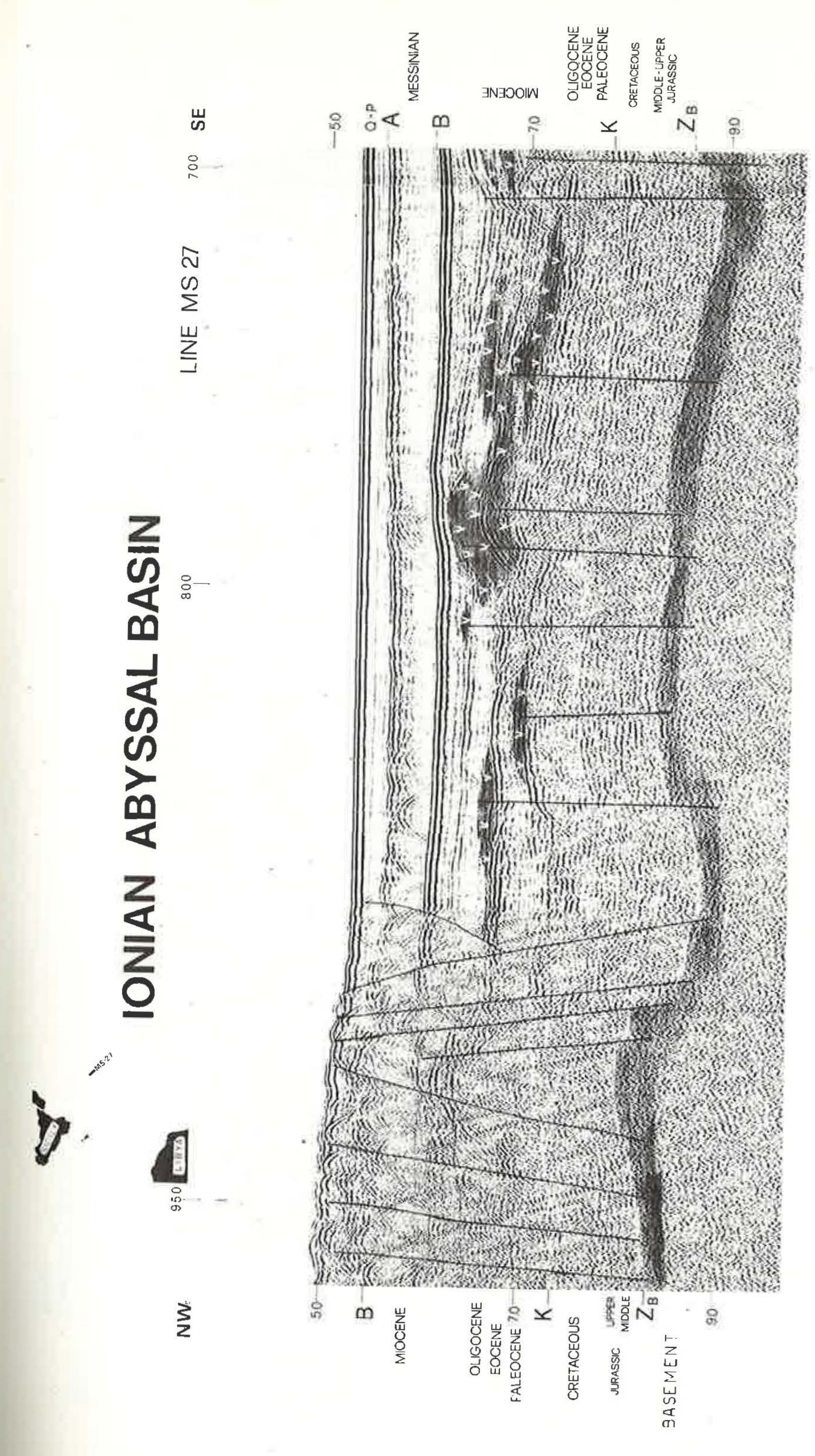


Fig. 14 — *Example of Interpreted Seismic Reflection Line in Ionian Abyssal Basin (Line MS-27; S.P. 970-695).* Extending the interpretation of Sirte Basin and Pelagian Sea Areas calibrated by boreholes to the Ionian Abyssal Basin, the hypothesis of Middle-Upper Jurassic sediments on a basaltic basement, fits very well on the entire seismic network of Ionian Basin. Evidence of extensional faults of "K" and "NQ" phases and of volcanic activity in Miocene.

IONIAN ABYSSAL BASIN

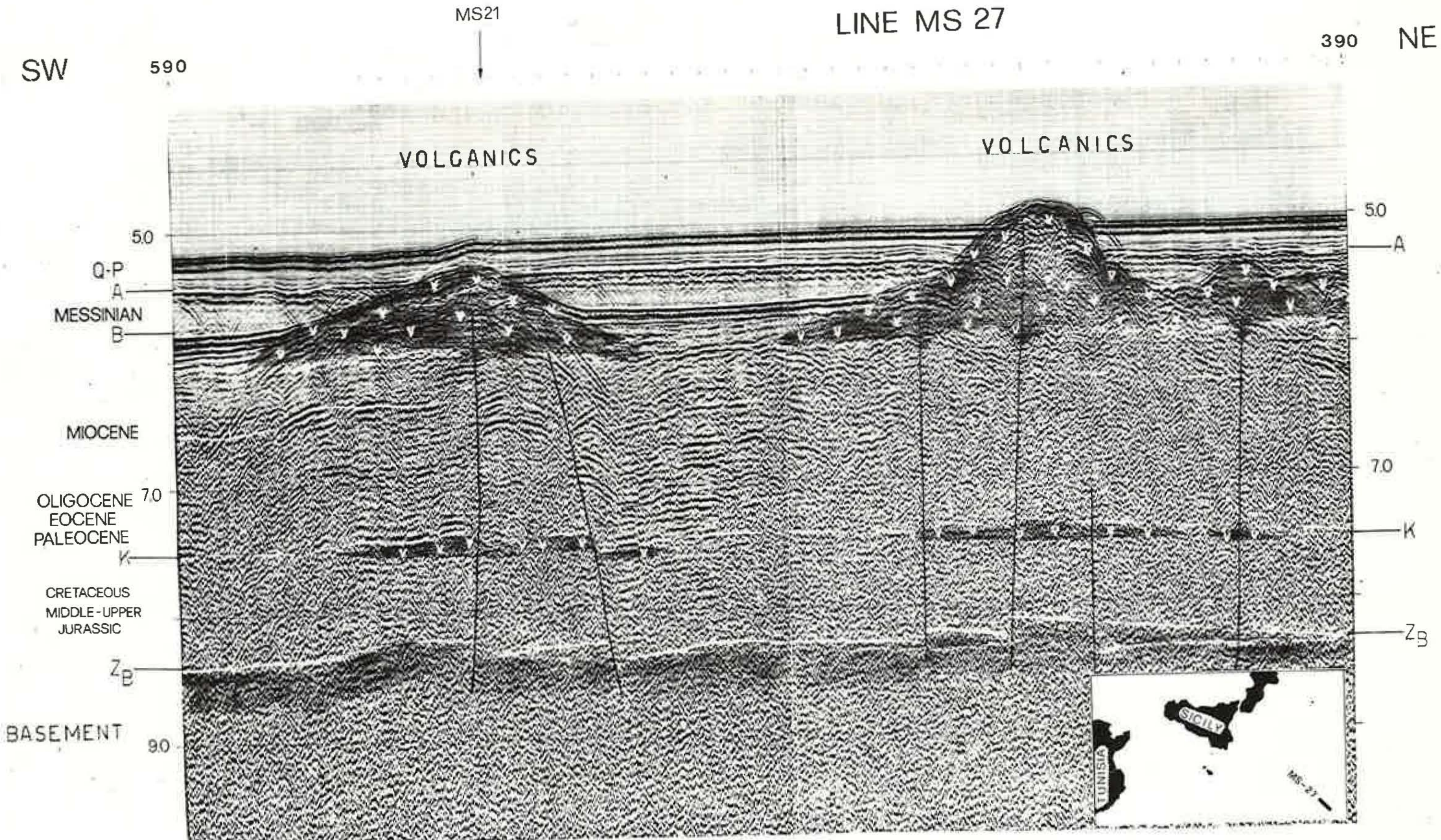


Fig. 15 — *Example of Interpreted Seismic Reflection Line in Ionian Abyssal Basin (Line MS-27; S.P. 590-390).* Evidence of faulting and volcanic activity associated with "K" and mainly "NQ" stretching phases. One volcanic show is outcropping with a small Sea Mount.

IONIAN ABYSSAL BASIN

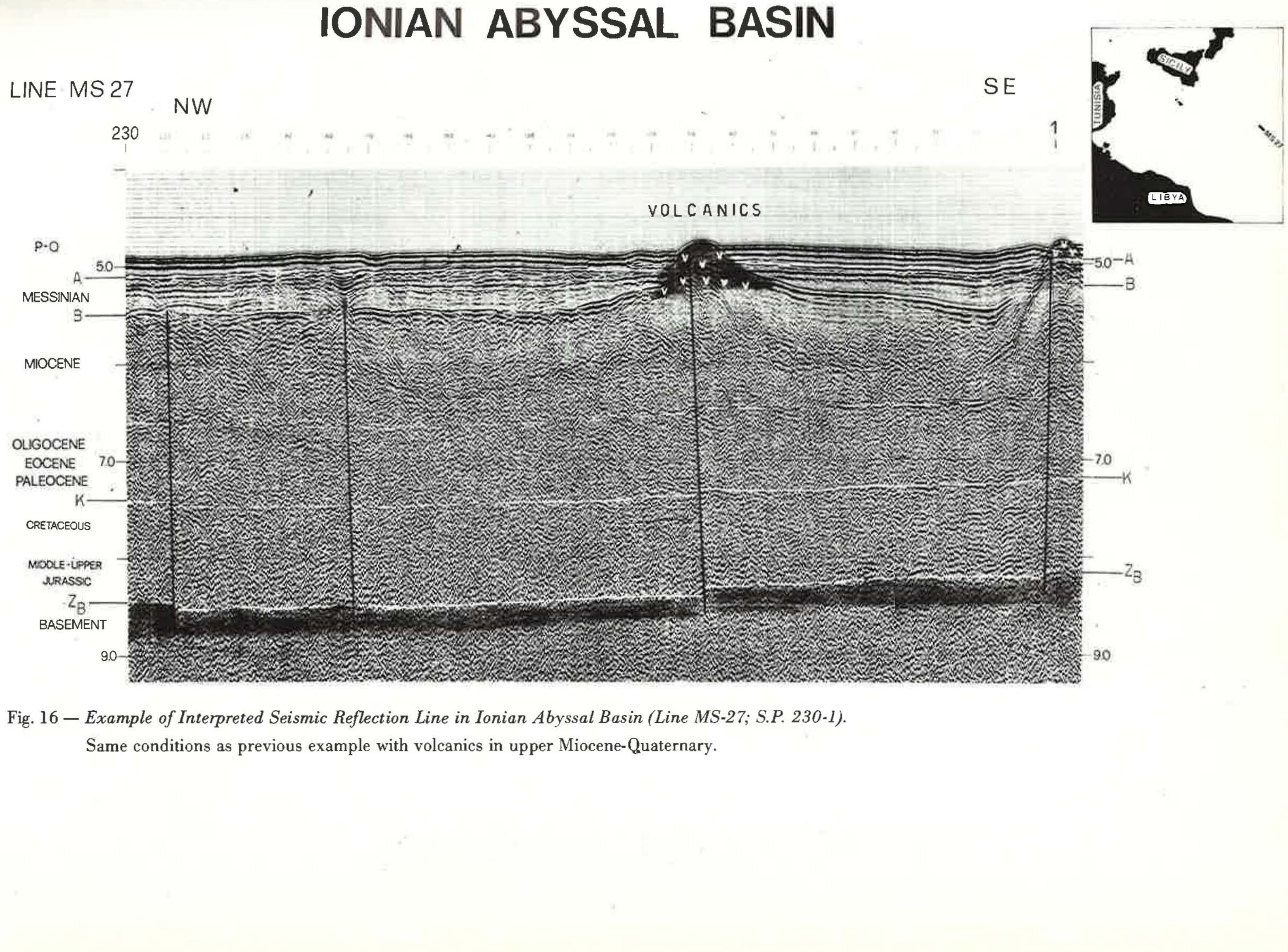


Fig. 16 — *Example of Interpreted Seismic Reflection Line in Ionian Abyssal Basin (Line MS-27; S.P. 230-1).* Same conditions as previous example with volcanics in upper Miocene-Quaternary.

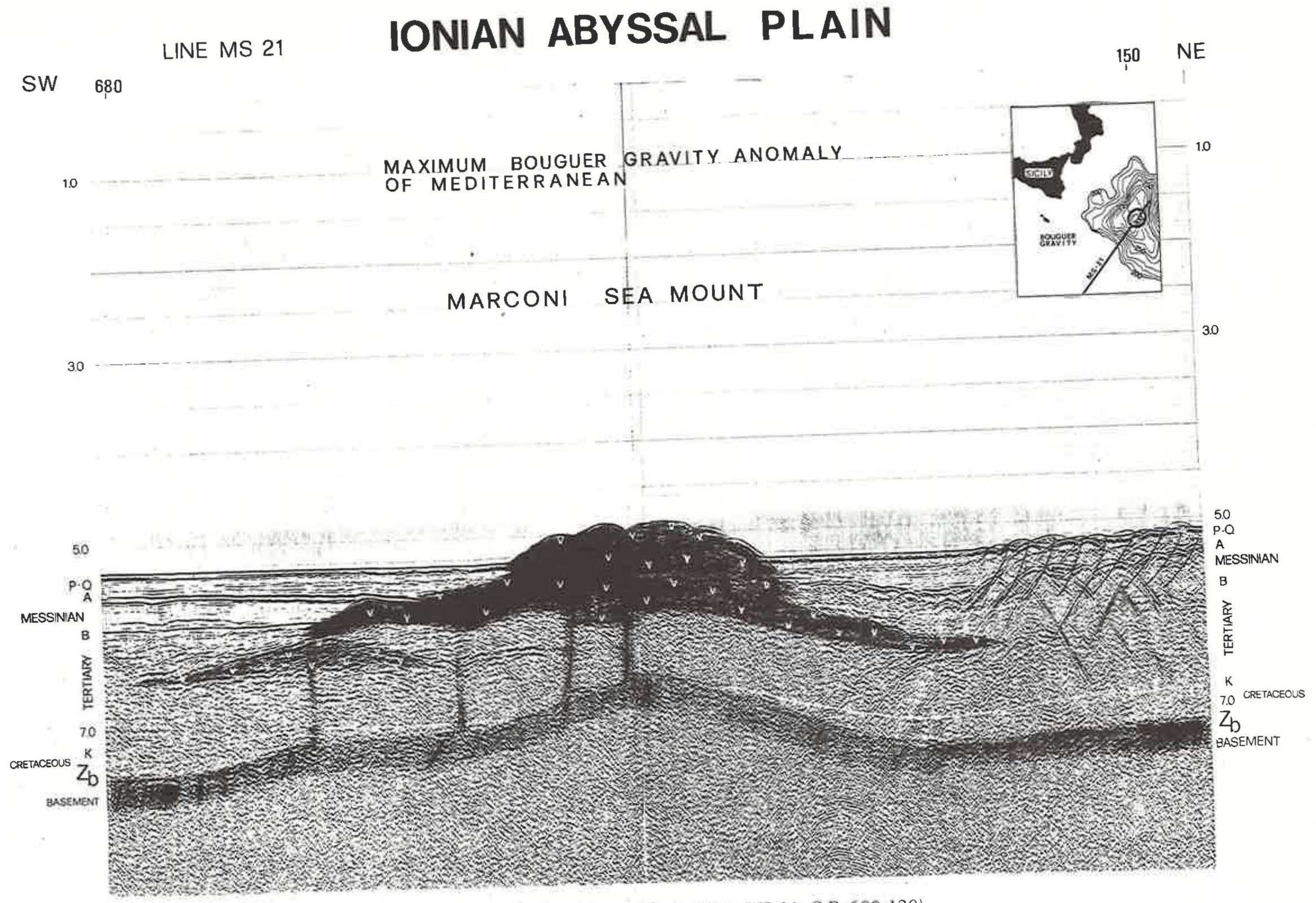


Fig. 17 — *Example of Interpreted Seismic Reflection Line in Ionian Abyssal Basin (Line MS-21; S.P. 690-120).* This part of Seismic Line MS-21 is located on the maximum Bouguer anomaly area (+ 310 mGal) of Central Ionian Basin. Evidence of prominent magmatic extrusions with a Sea Mount here named for the first time "Marconi Sea Mount" dedicated to one of the World's greatest scientists. Sedimentary sequence is considerably thinning and basement uplifting.

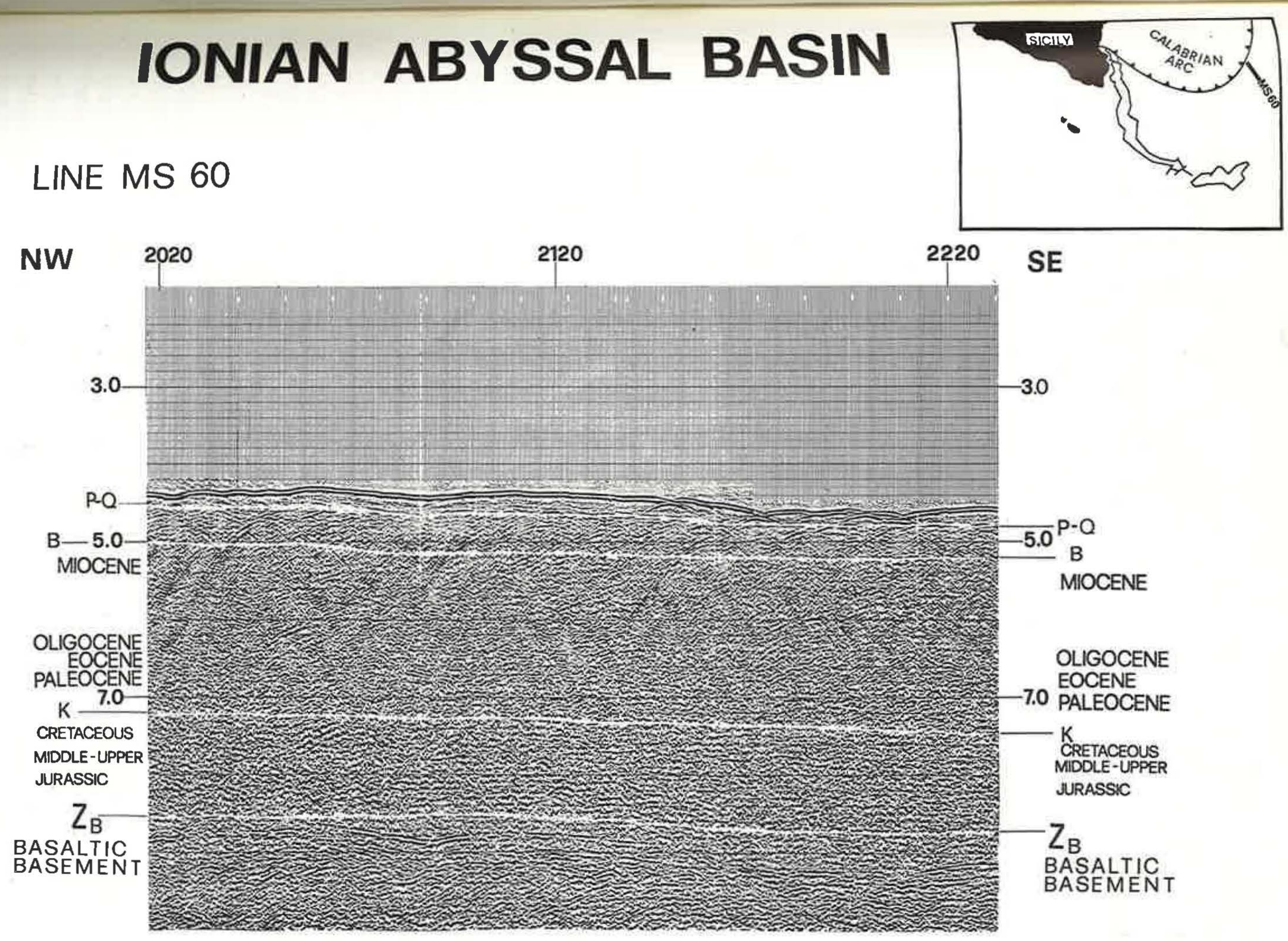


Fig. 18 — *Example of Interpreted Seismic Reflection Line in Ionian Abyssal Basin Near the Outer Limit of Calabrian Arc (Line MS-60; S.P. 2020-2225).* This and the next six Figures show the entire line MS-60, which crosses the whole Ionian part of Calabrian Arc. In this Figure are shown the typical flat conditions of the Ionian Abyssal Basin with sediments from Middle-Upper Jurassic to Quaternary.

maximum anomaly of the Mediterranean (Finetti-Morelli, 1973) of +310 mGal exists.
Such a very high value cannot be explained with models of continental crust or of intermediate types. Here, a very consistent thinning of the Mesozoic sequence and uplifting of the basement *(Fig. 17)* and prominent volcanic activities with a Sea mount — to which we give the name of "Marconi" — took place.

h) Recent Deep Seismic Sounding investigations with seabottom seismographs indicate in the Ionian, off the maximum Bouguer anomaly, an oceanic crust with a Moho depth of about 17 km. This value is in agreement with our calculations and we expect a further crustal thinning at the Marconi sea mount area, up to a minimum of about 13-14 km *(Fig. 34)*. This crustal model may now explain the Bouguer anomaly very well.
i) Assuming a model which postulates a crustal opening in the Middle Jurassic as would indicate all the above listed arguments, all data used for this study fit very well, and in any case much better than models of continental or intermediate crusts.
j) The Apulian platform, on its SW side, in the Ionian Sea, is affected by clear extensional geodynamics. The extended area with faults and back-tiltings is about 100 km wide. The latest movements occurred in recent times. Such a deformation pattern of the Apulian slope seems well in agreement with a model of a still moving passive margin.

Regarding the proposed crustal opening it is to be observed that the regional seismic exploration of the OGS here interpreted, does not indicate the existence of a mid-oceanic ridge, unless more detailed seismic control extends the Marconi feature north-westward and south-eastward. Probably, the hypothesis of the detachment and drifting of the Apulian (or Adriatic) plate, without mid-oceanic ridge creation, is the more correct interpretation.

2.4 — Apulian Platform

The Apulian platform is characterized by a very thick Mesozoic sedimentary sequence, continuous from the Permo-Triassic to the Upper Cretaceous in the southern part, and with the Upper Cretaceous missing in the northern one (about north of 41° parallel).

A deep borehole drilled in the Southern Apulia (Ugento 1) indicates about 4000 metres of Cretaceous over Jurassic. In the northern part (area of Canosa positive gravity anomaly) geophysical data indicate a very thin Lower Cretaceous (less than 200 metres) overlaying a Jurassic sequence about 4000 metres thick. So, in southern onshore Apulia we expect the top Triassic at about 8 km depth.

Lithologically, the Mesozoic succession is almost completely characterized by monotonous carbonate sequences, constituted by predominant limestone in the Upper Cretaceous and Dolomite in the Lower Cretaceous, Jurassic and Triassic. The Upper Triassic evaporite, well evident in the Adriatic from seismic data and constituted by halite in the Southern Adriatic basin and in the Peloponnesus area, on the contrary is not so evident in the Apulian seismic reflection data. From refraction seismics it is possible to discriminate in Apulia a very high velocity refractor of about 7.0 km/s, attributable to an anhydrite interval encountered in a borehole of the Gargano area at about 2200 metres below sea level, but much deeper in the Apulian peninsula.

Structurally, the emerged Apulian platform is rather tabular or very slightly ondulated. The Gargano feature, very probably, is essentially a diapire-like structure generated by horizontal movements, with transform and shear faults along with the Triassic evaporitic interval. Clear seismic evidence of a transcurrent fault, crossing the Gargano and Southern Adriatic area exists for the Gargano fault *(Plate - III)*. Evidence of

a regional transform fault can also be found for the Kefallinia fault which limits the Apulia platform and the Hellenic arc in the NE Ionian Sea.

The Apulian platform extends considerably south-eastward, up to the Kefallinia Island area. In the Adriatic it extends irregularly from about 20 to 45 km and then across a steep slope passes to much thinner sequences, probably corresponding to a deeper deposition after the "J" extensional phase of the Middle Jurassic. On the Ionian side clear evidence of extensional geodynamics exists *(Fig.s 4 & 5)*. Here, the faulted slope connects the thick platform area with the relatively thin Mesozoic sequence of the Ionian abyssal basin interpreted as paleo-oceanic crust.

All the reconstructed structural data from the Apulian platform and surrounding vast area point to the convincing conclusion that Apulia, after its detachment from the Africa megaplate has drifted north-eastward and nowadays, due to the horizontal pressure of Dinarides and Hellenides on one side and of Apennine on the other, is moving anticlockwise along the Kefallinia and Gargano faults. Seismicity of the area is well in agreement and fully explained by such a postulated rotation.

2.5 — Southern Adriatic Basin

There is a consistent geological difference between the area of the central-northern Adriatic with shallow water and the area of the Southern Adriatic basin *(Plate III)* with deep water. A substantial analogy probably existed between these two areas from the Permo-Triassic until the Lower Jurassic, with a relatively thick dolomitic sequence and an evaporitic succession in the Upper Triassic. This evaporite is mostly anhydritic in the central northern Adriatic, while in the southern basin a thick halite precipitation is indicated by seismic data.

After the main "J" extensional phase of the Middle Jurassic, which occurred in the central-eastern Mediterranean, very probably, also the southern Adriatic, which is the marginal basin of the Apulian (Adriatic plate), was affected by the stretching activity with consequent subsidence and depositional change.

Geophysical data indicate that from the Jurassic (probably from the Middle-Upper Jurassic) until the end of the Oligocene the sedimentary sequence is relatively condensed. In the Miocene, due to the high deposition rate connected to the compressional phase of Dinarides, the sequence becomes progressively very thick from west to east (Finetti-Morelli, 1973: *Fig. 25*).

At the top of the Lower Cretaceous in the Southern Adriatic basin, as well as in the greater part of the Pelagian, Ionian and Eastern Mediterranean Seas, it is possible to identify a continuous characteristic good to fair reflector corresponding to the "Marne a Fucoidi" layer. This reflector is generally associated with a relatively thin interval of Marls interbedded with a carbonate sequence.

2.6 — Calabrian Arc

To observe the deformational process that took place in the Ionian part of the Calabrian Arc it is convenient to follow the entire interpreted Seismic line MS-60 from south-east to northwest *(Fig.s 18, 19, 20, 21, 22, 23 & 24)*. The first figure *(Fig. 18)* shows the undeformed area of the Ionian abyssal basin just off the outer limit of the Calabrian arc. Here the sedimentary crust is the typical one, interpreted as paleo-oceanic, already seen in previous figures *(Fig.s 14, 15, 16 & 17)*, and characterized by a relatively thin Mesozoic (about 1.3 sec reflection time), overlain by a thick tabular Tertiary Sequence (more than 2.4 sec) mainly constituted by Miocene.

Successive figures *(Fig.s 19 to 24)* show the arcuated area deformed by the Neogene-Quaternary compressional geodynamics. In *Fig. 19*, at the outer limit of the Calabrian arc, the shearing plane corresponds to the base of Messinian evaporite. This

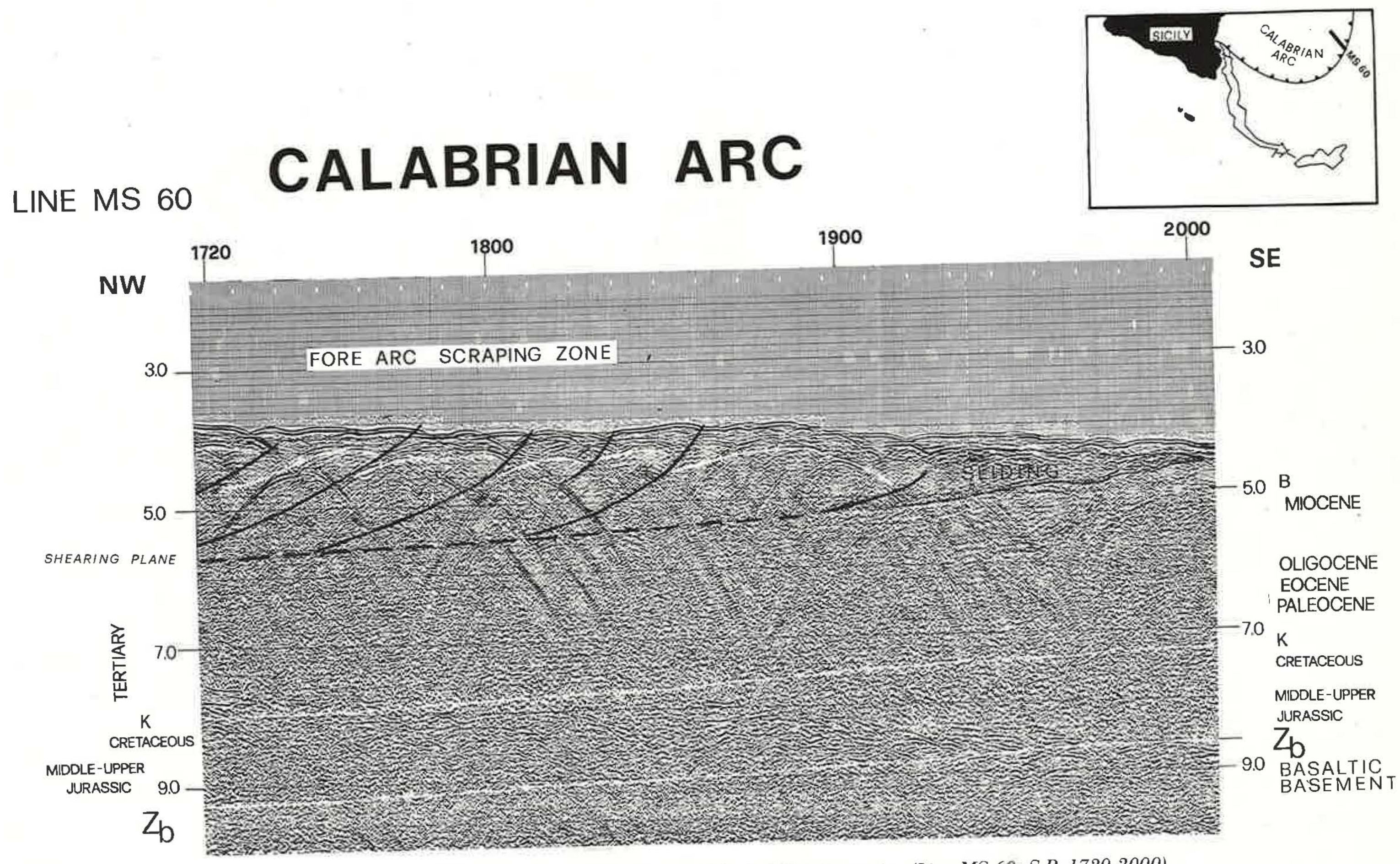


Fig. 19 — *Example of Interpreted Seismic Reflection Line On the Most External Part of Calabrian Arc (Line MS-60; S.P. 1720-2000).* From flat conditions of Ionian Abyssal Basin one passes to the sliding interval, in front of the Arc and then to the beginning of the Fore Arc Scraping Zone. A shearing plane at the base of Messinian is evident and deepens progressively.

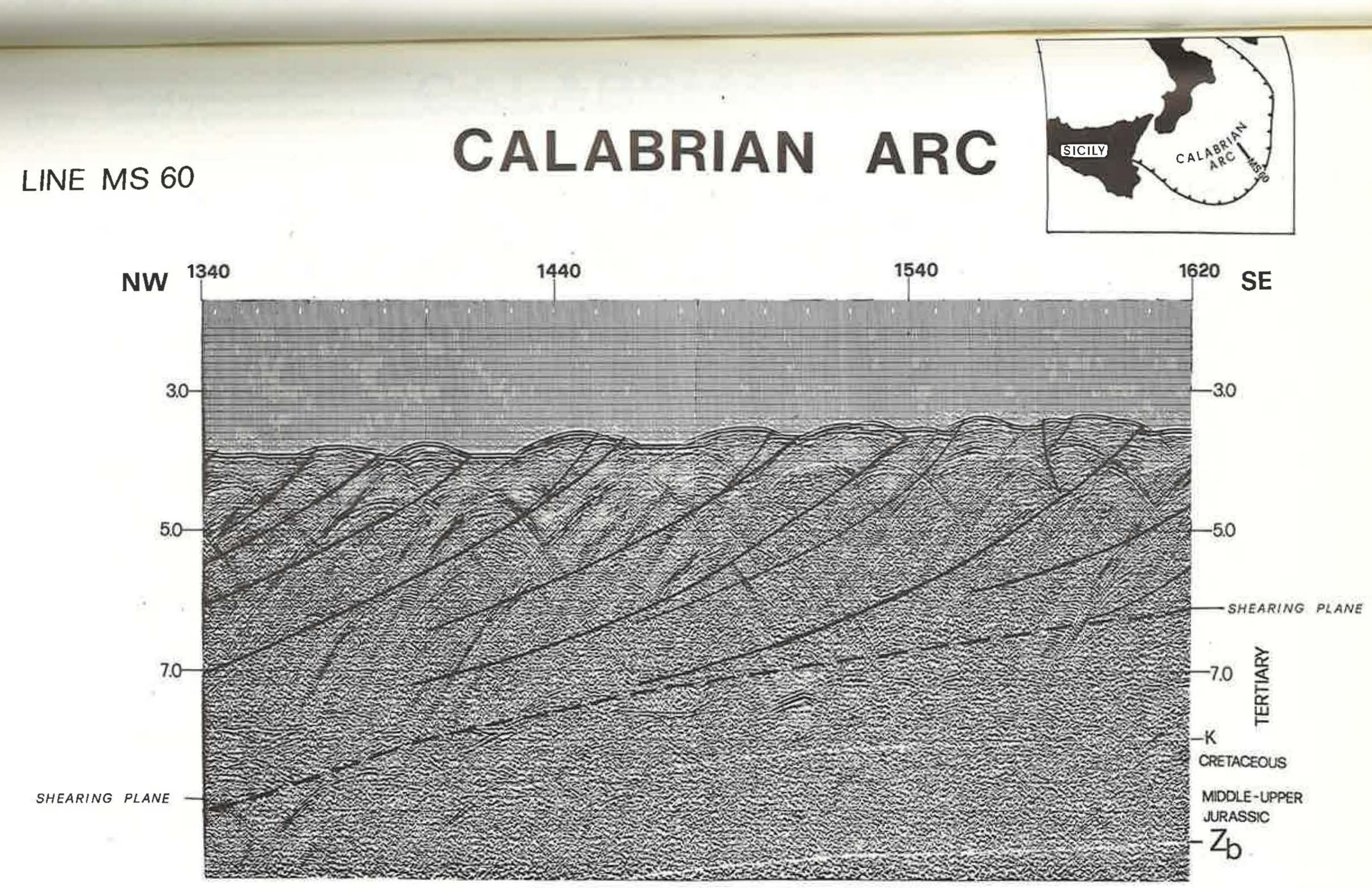


Fig. 20 — *Example of Interpreted Seismic Reflection Line Across Calabrian Arc (Line MS-60; S.P. 1340-1620).* Fore Arc scraped blocks on a shearing plane progressively deepening inward, from about 6 to 8 seconds.

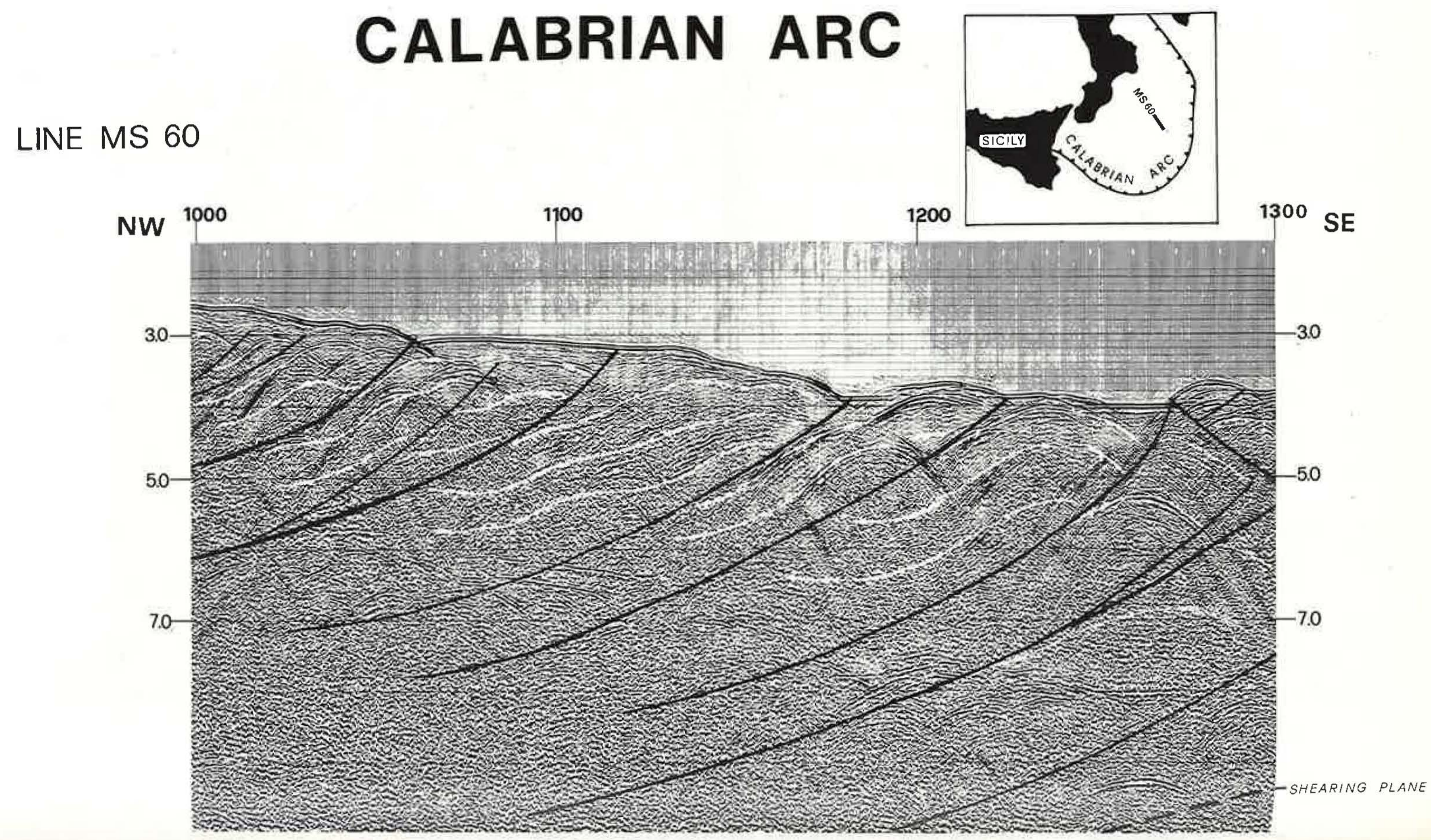


Fig. 21 — *Example of Interpreted Seismic Reflection Line Across Calabrian Arc (Line MS-60; S.P. 1000-1300).*
Shearing plane limiting base of scraping disappears below the bottom of section, involving deeper layers of Mesozoic in deformation process.

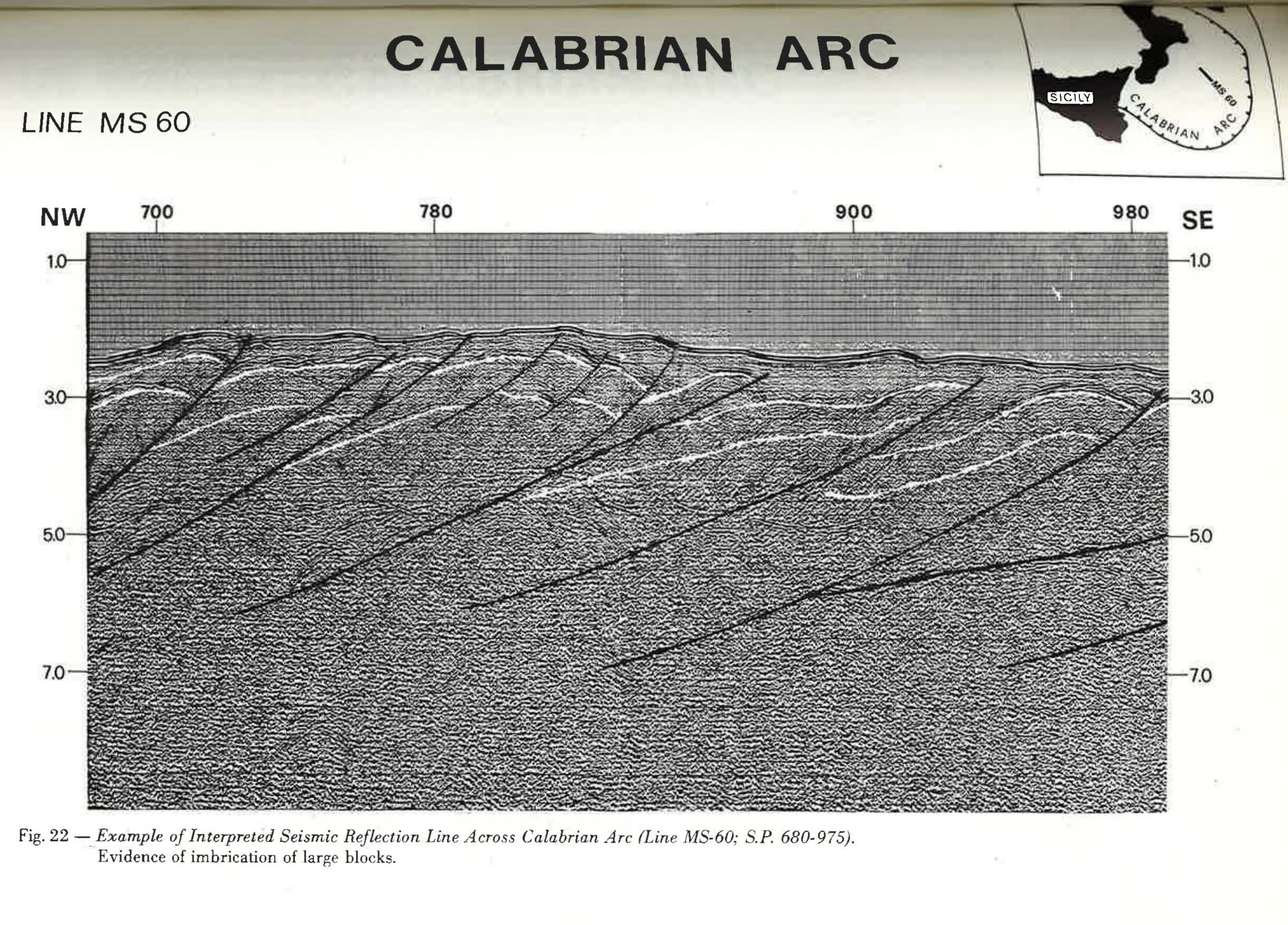
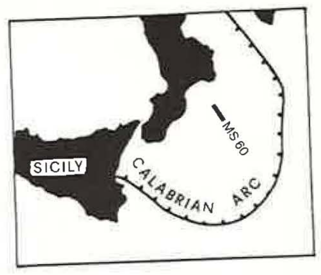


Fig. 22 — *Example of Interpreted Seismic Reflection Line Across Calabrian Arc (Line MS-60; S.P. 680-975).*
Evidence of imbrication of large blocks.

CALABRIAN ARC



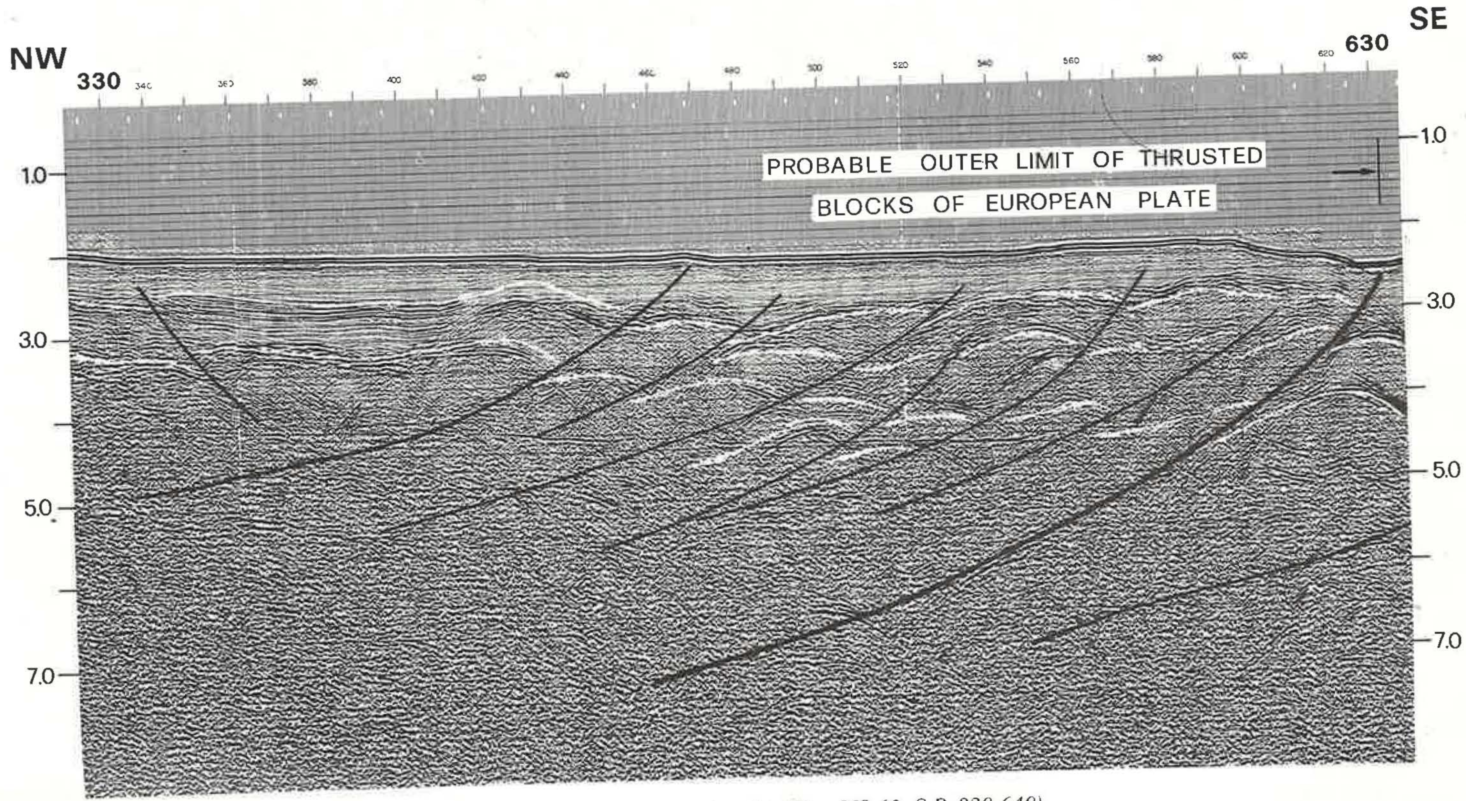


Fig. 23 — *Example of Interpreted Seismic Reflection Line Across Calabrian Arc (Line MS-60; S.P. 320-640).* Probably Crystalline-Metamorphic and Mesozoic Blocks of European Plate are imbricated from S.P. 320 to about 630. Assuming such interpretation, S.P. 630 should correspond to the Trench Zone of Calabrian Arc, morphologically not so evident as the Hellenic Trench.

LINE MS 60

CALABRIAN ARC

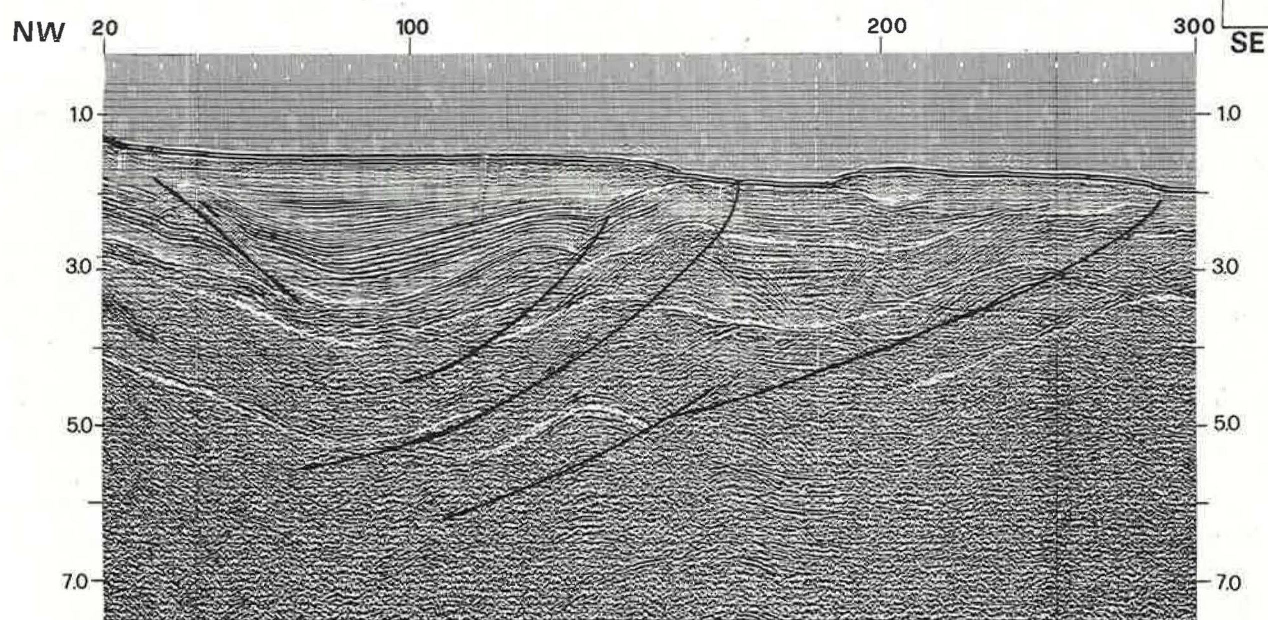


Fig. 24 — *Example of Interpreted Seismic Reflection Line Across the Calabrian Arc (Line MS-60; S.P. 20-300).* Imbrication of large blocks which includes the Crystalline-Metamorphic and Mesozoic.

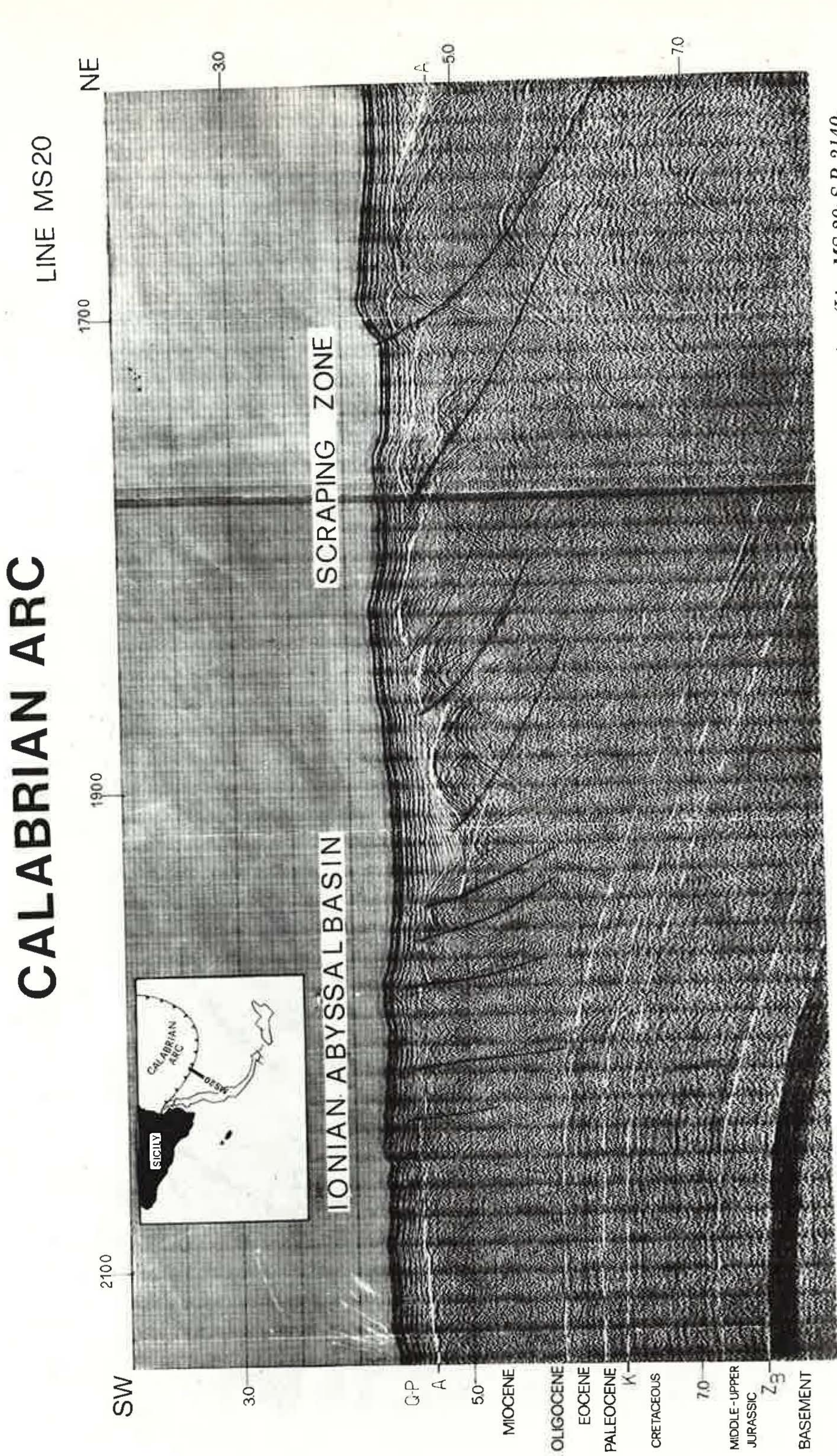


Fig. 25 — Example of Interpreted Seismic Reflection Line Showing the Overthrusting of Calabria Arc on Ionian Abyssal Basin Area (Line MS-20; S.P. 2140-1610).
On SW. part of Calabrian Arc the slope of the underthrusting Ionian sequence is much more accentuated than on southern part (Compare e.g. with Figure 19).

plane then deepens progressively *(Fig.s 20 & 21)*, involving the entire Tertiary sequence ad the Upper Mesozoic. On *Fig. 22* it is not possible to follow it any more because of the thick thrusted blocks. Very probably, after about the S.P. 1000, as indicates also the Bouguer gravity gradient, the shearing plane enters the greater part of the total sedimentary sequence.

In the outer part of the arc *(Fig. 19)*, from about S.P. 2000 to 1900, there is the frontal sliding allochthonous or melange. Such gravitative sliding deposits can be found in the foredeeps in front of every major thrusted block, or where a certain slope of Messinian and soft sediments exists. From S.P. 1900 to about S.P. 630 *(Fig.s 19 to 23)* imbricated blocks detached from the underthrusting African plate are explored and shown. If our interpretation regarding the crustal opening of the Ionian is correct, we expect that these blocks generally do not include older sediments than Middle Jurassic, except possible continental fragments which persisted after the drifting of the Apulian plate.

So, the area from S.P. 1900 to 630 would correspond to the fore-arc scraping zone which seismically seems quite similar to other more classic scraping zones of the Indian and Pacific oceans. In the Calabrian arc the existence of a trench zone like for example, in the Hellenic arc is not immediately evident. But, a careful examination of the available geophysical data (seismic ad gravity) combined with known geological, borehole and physiographic data may distinguish on *Fig.s 23 & 24*, from S.P 630 to 20 the area where crystalline-metamorphic blocks and Mesozoic blocks of European plate are overthrusted on the forearc scraping zone. In this case the trench zone of S.P. 630 is very close and associated with subhorizontal or slightly dipping fault planes. The sea bottom surface, across the interpreted trench zone, drops down about 0.4 sec. or about 300 m. *(Plate 1)*.

While in the southern extremity of the Calabrian arc the Ionian crust is underthrusting with a very gently dipping plane *(Fig.s 19 & 20)*, in the SW part *(Fig. 25)* as well as in the SE one, the Ionian sequence underthrusts the Calabrian arc with a much more accentuated slope. Observing these and other general aspects of the compressional deformation, it seems possible to argue that in recent geological time (Plio-Quaternary) the main component on the relative Africa-Europe movement in the Ionian Sea is not the N-S, but the SW-NE one. This fact determines now a shortening of the space of the Calabrian arc from Sicily-Malta escarpment to the Apulian margin with consequent restriction of arc width.

The same main component of the movement determines compression, overthrustings and shortening of the Ionian abyssal area in front of the Mediterranean ridge and of the ridge area. On the other side of the Hellenic arc, in the Levantine Sea, for this reason, the main consequent deformation is the gravity sliding.

2.7 — Hellenic Arc

The Ionian part of the Hellenic arc shows a regional structure very similar to that of the Calabrian arc. For a more complete geophysical documentation, in addition to the *Fig.s 26, 27, 28, 29 & 30* we refer also to Finetti (1976).

In *Fig. 26*, Line MS-33 shows the structural and time stratigraphic relationships between the Ionian abyssal basin and the Mediterranean ridge. The Mediterranean ridge can be considered in summary the fore-arc scraping zone of the Hellenic arc, formed entirely by detached ad imbricated blocks of sedimentary crust of the Ionian Sea. The Messinian, including the salt layer, is here relatively thick with respect to the Ionian Late Miocene evaporite sequence. In *Fig. 28* the shearing plane coincides practically with the base of the Messinian salt. Then in *(Fig. 29)* entering more in the Mediterranean ridge, this plane deepens progressively and involves older sediments. *Fig.s 27 & 30* show the structural conditions where relatively big blocks are imbricated.

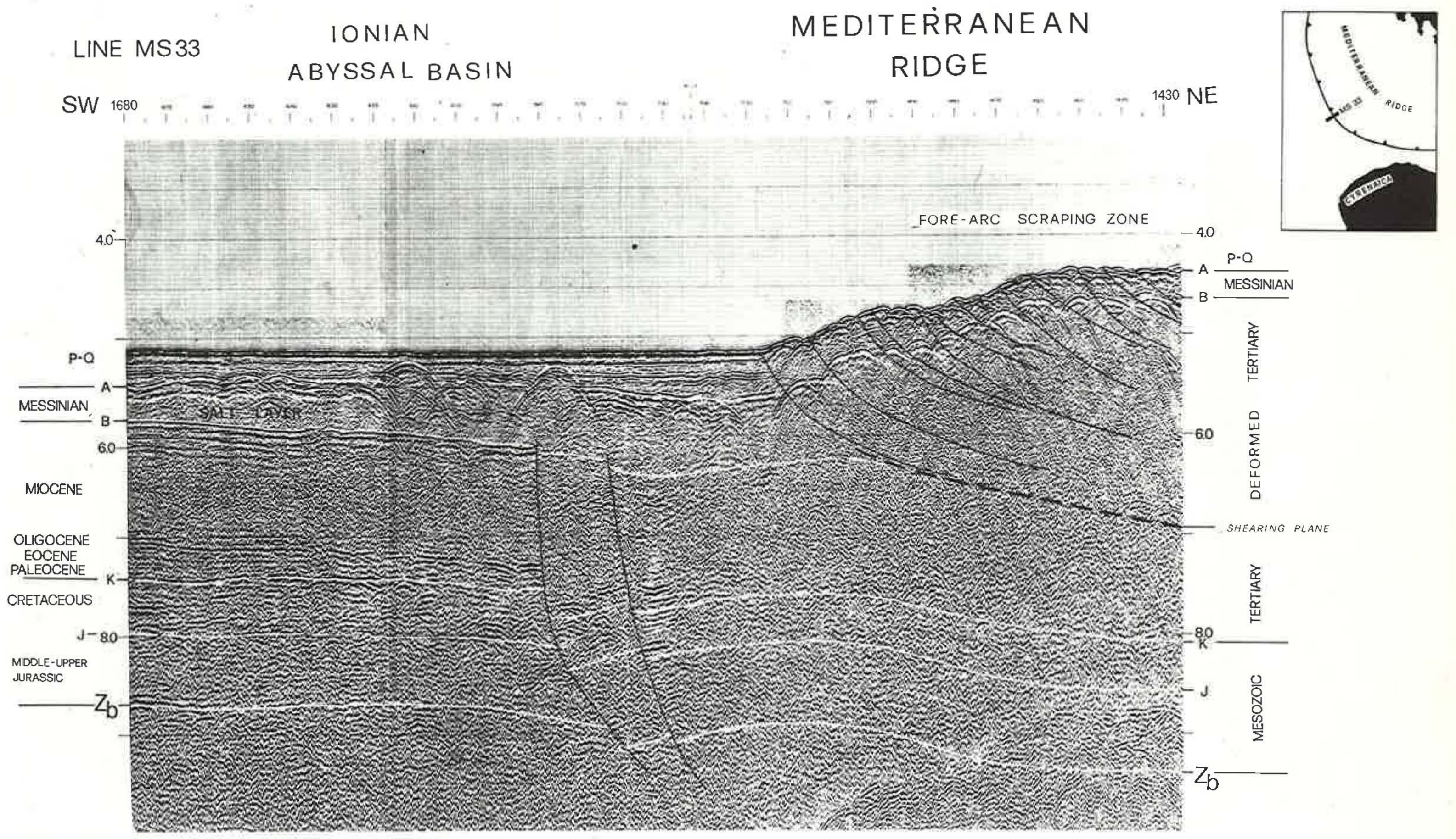


Fig. 26 — *Example of Interpreted Seismic Reflection Line Showing the Contact Between Ionian Abyssal Basin and Mediterranean Ridge (Line MS-33; S.P. 1680-1425).*
Messinian interval "AB" is relatively thick and forms Salt Domes in front of the Scraped Zone. In this outermost part the shearing plane occurs along the Messinian interval.

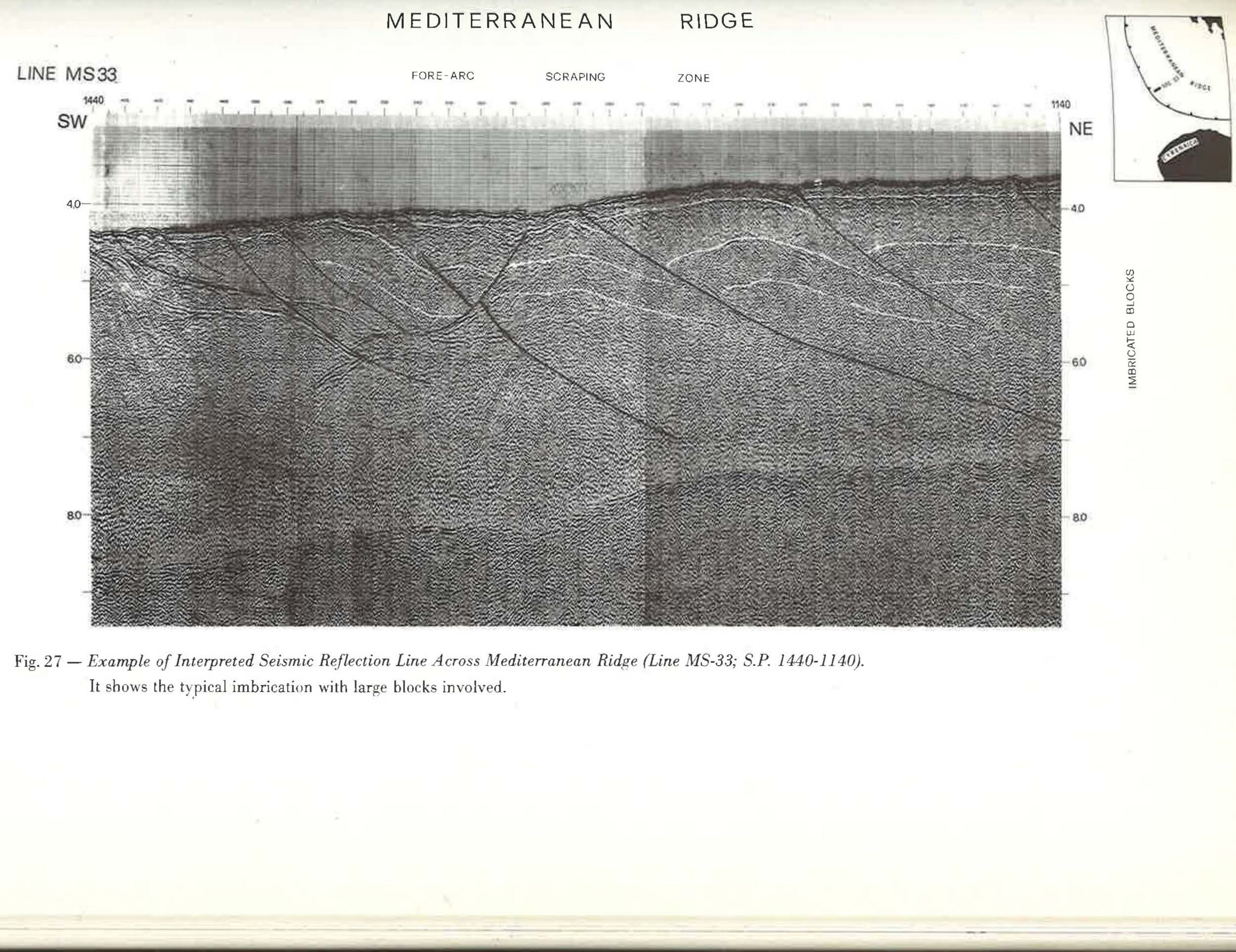


Fig. 27 — *Example of Interpreted Seismic Reflection Line Across Mediterranean Ridge (Line MS-33; S.P. 1440-1140).*
It shows the typical imbrication with large blocks involved.

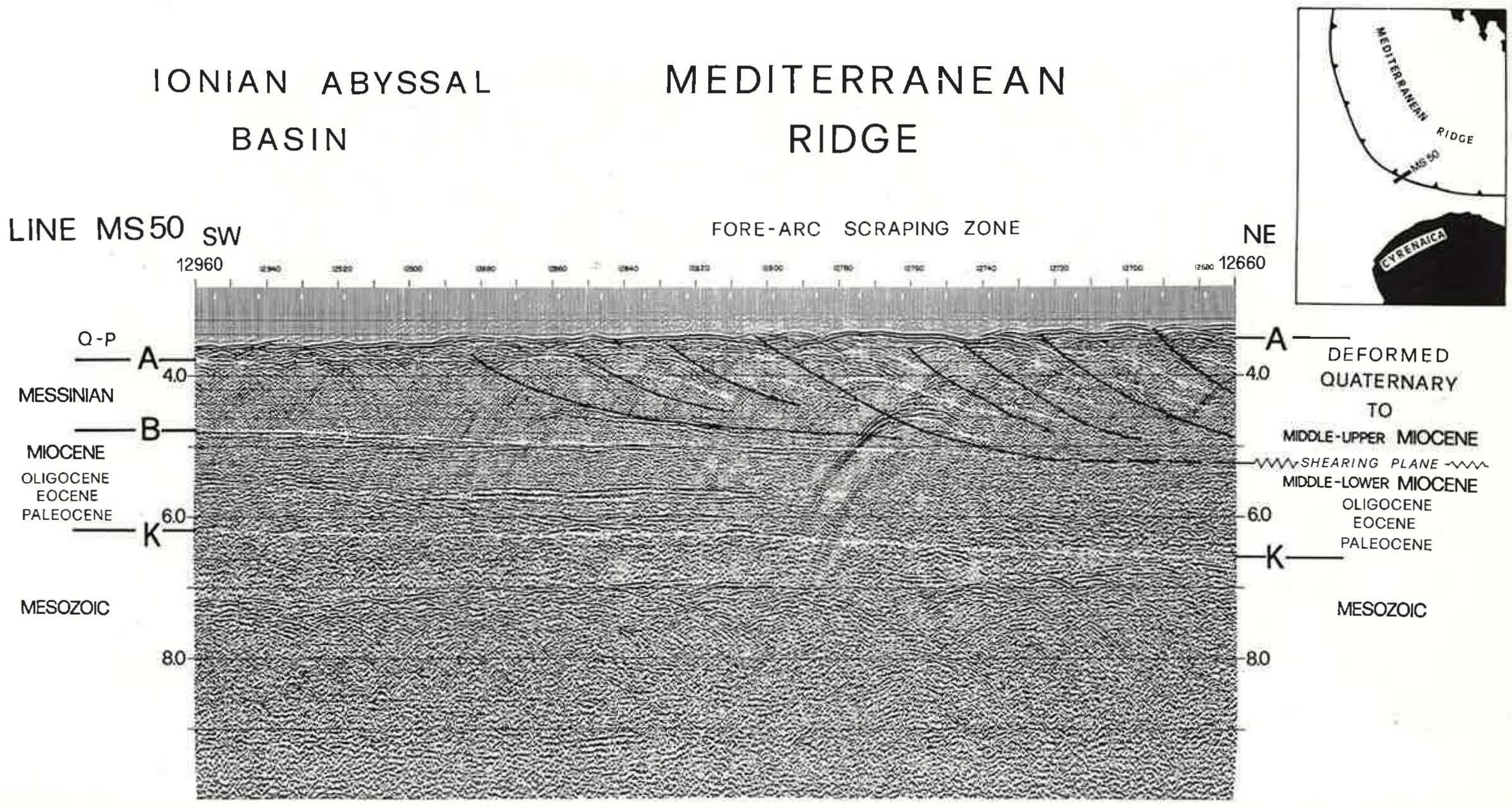


Fig. 28 — *Example of Interpreted Seismic Reflection Line Showing the Contact Between the Cyrenaican Margin and the Mediterranean Ridge (Line MS-50; S.P. 12960-12660).*
Thick Messinian (near one second) and beginning of Fore Arc Scraping Zone with shearing plane flat and sloping gently.

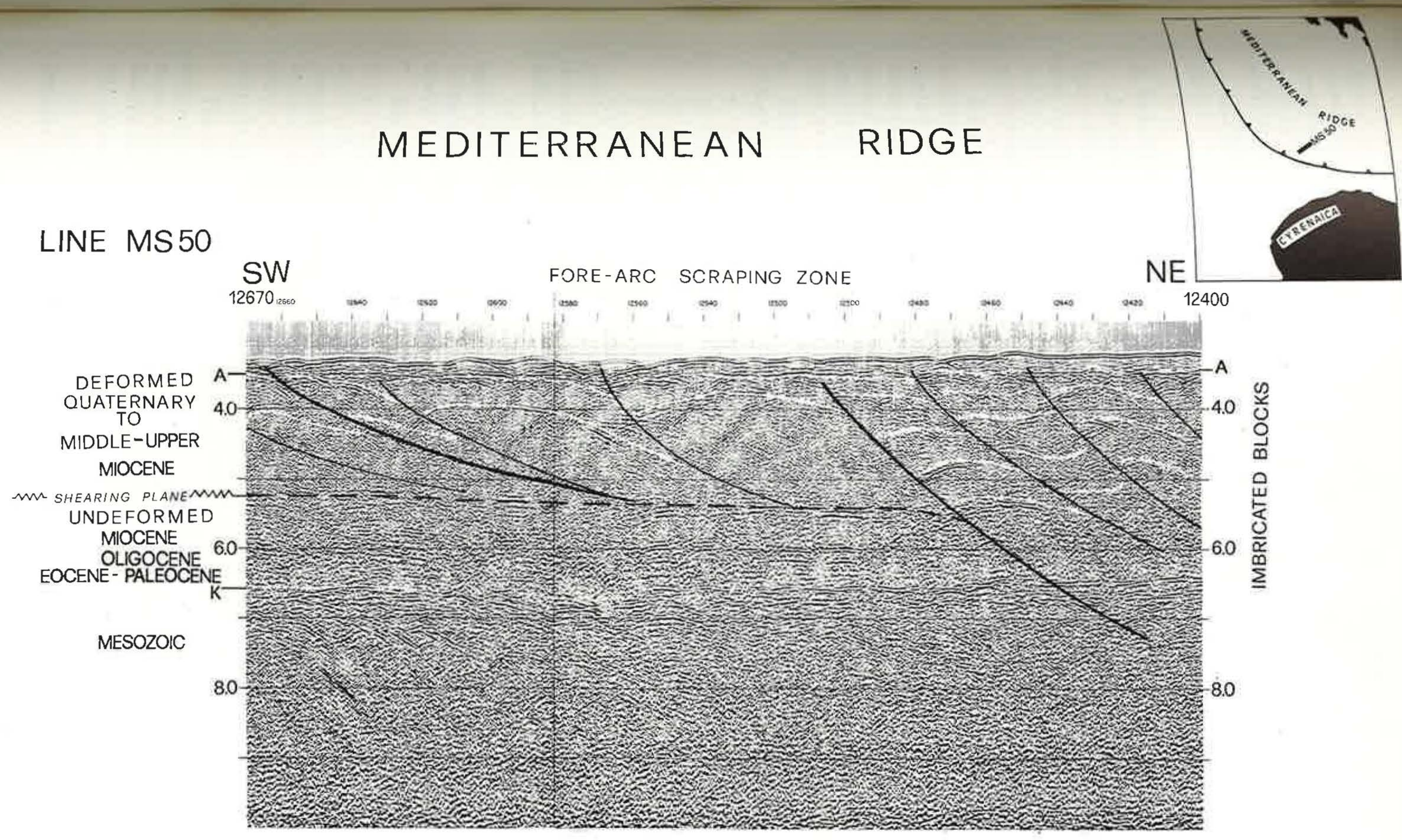


Fig. 29 — *Example of Interpreted Seismic Reflection Line Across Mediterranean Ridge (Line MS-50; S.P. 12670-12400).*
It shows the scraping process, and around S.P. 12470 the faulting commences to involve Mesozoic.

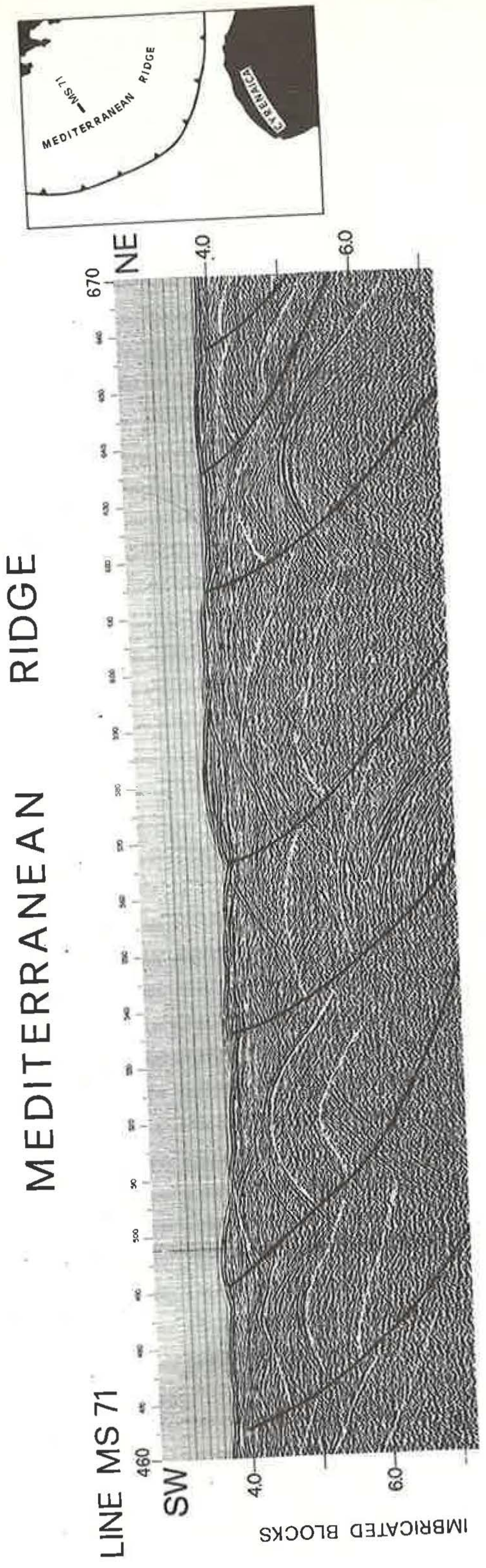


Fig. 30 — Example of Interpreted Seismic Reflection Line Across Mediterranean Ridge (Line MS-71; S.P. 460-670).
Typical compressional deformation with imbrication of blocks and deep faults.

In the Hellenic arc the existence of a trench zone *(Plate - III)* separating the thrusted blocks of European plate over the scraped and imbricated blocks of the underthrusting African plate is well evident. From geophysical data it seems possible to say that the crustal layer, separating the imbricating blocks and the underthrusting, corresponde probably to the paleo-oceanic basement. In fact, no remarkable magnetic anomalies exist in the Mediterranean ridge. Therefore it seems that imbrication involves only sedimentary layers.

In *Plate II* the reconstructed geological cross-section of the Mediterranean ridge and the Ionian abyssal basin is shown. Moho discontinuity is calculated from gravity.

3. Volcanic activity

In the previous paragraphs, we have commented on the volcanic activities and their space distribution on the various studied geological provinces. For a more organic view, this important argument is now more specifically examined with the purpose of following the time and space distribution of volcanism and of understanding connected geodynamical meanings.

Assembling all the numerous known volcanic shows outcropping, checked by boreholes, or deduced from geophysical exploration, a function of igneous activity against geological time from Permo-Triassic until the present with an arbitrary scale is compiled *(Fig. 32)*. In this figure the plotted intensity of volcanic activity is obtained taking into account the total thickness of igneous intervals occurring in a given province, in the considered geological time, and the space distribution density of the same area.

The following four main phases of igneous activity have been recognized in the Pelagian and Ionian Seas during about the last 230 M y.:

1) Middle-Upper Triassic ("T")
2) Middle-Jurassic ("J")
3) Middle-Upper Cretaceous ("K")
4) Middle-Upper Miocene to Quaternary ("NQ")

These phases are associated with corresponding parossistic periods of extensional geodynamics occurred on a more or less wide part of the studied area, or on a determined province of it. In *Fig. 31* the space distribution of the volcanic activities with indication of the corresponding extensional phase is shown.

This time-space distribution is based on all the most important data until now gathered. It is evident that further explorations may improve the knowledge. In some areas, scarcely known at present, it is possible to expect event consistent modifications, and/or additional activities with respect to the present information.

The diagram of *Fig. 32* indicates the four main extensional phases recognized. This does not mean that between a phase and the successive one completely quiet conditions occurred. A main phase is intended as a geological interval of time during which remarkable geodynamical (rifting) processes took place on a wide area or along a regional fault. In between each phase the geodynamic activity produced, in a given province, more moderate deformations, but the activity did not necessarily cease completely.

The first phase "T" produced its checked effects on the Sicily Malta area with frequent basaltic intervals interbedded with Middle-Upper Triassic sedimentary sequences *(Fig. 31 & Plate IV)*. Very probably, also in the Gabes-Tripoli-Misurata basin a stretching activity occurred. We have no information, but we suppose activity of this phase also in the Sirte trough area.

As already mentioned above, in the Middle-Jurassic the most impressive and prominent volcanic activity of the Sicily-Malta area took place. Practically, on a large

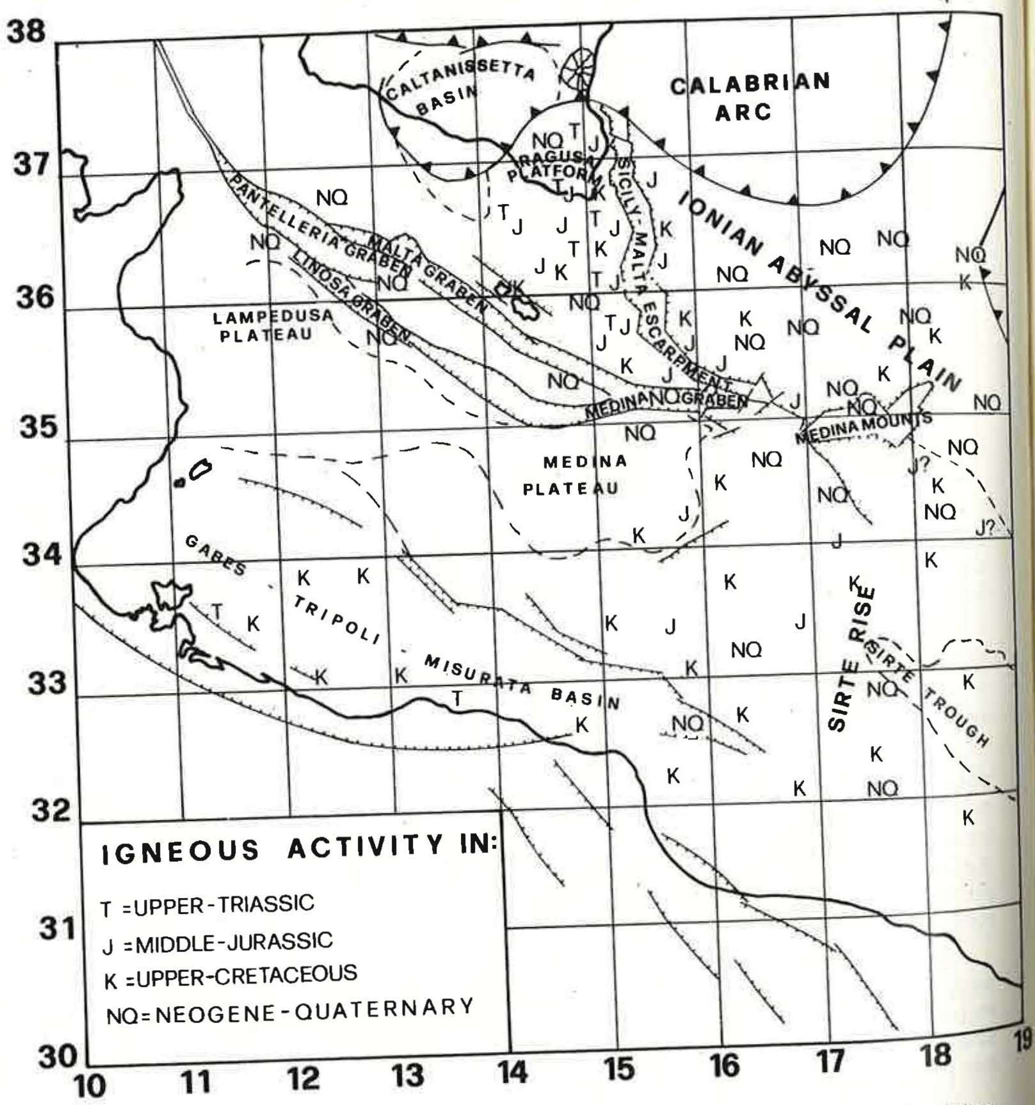


Fig. 31 — *Space-Time Distribution of Main Igneous Activities Checked by Boreholes and/or Inferred from Seismic and Magnetic Information.*

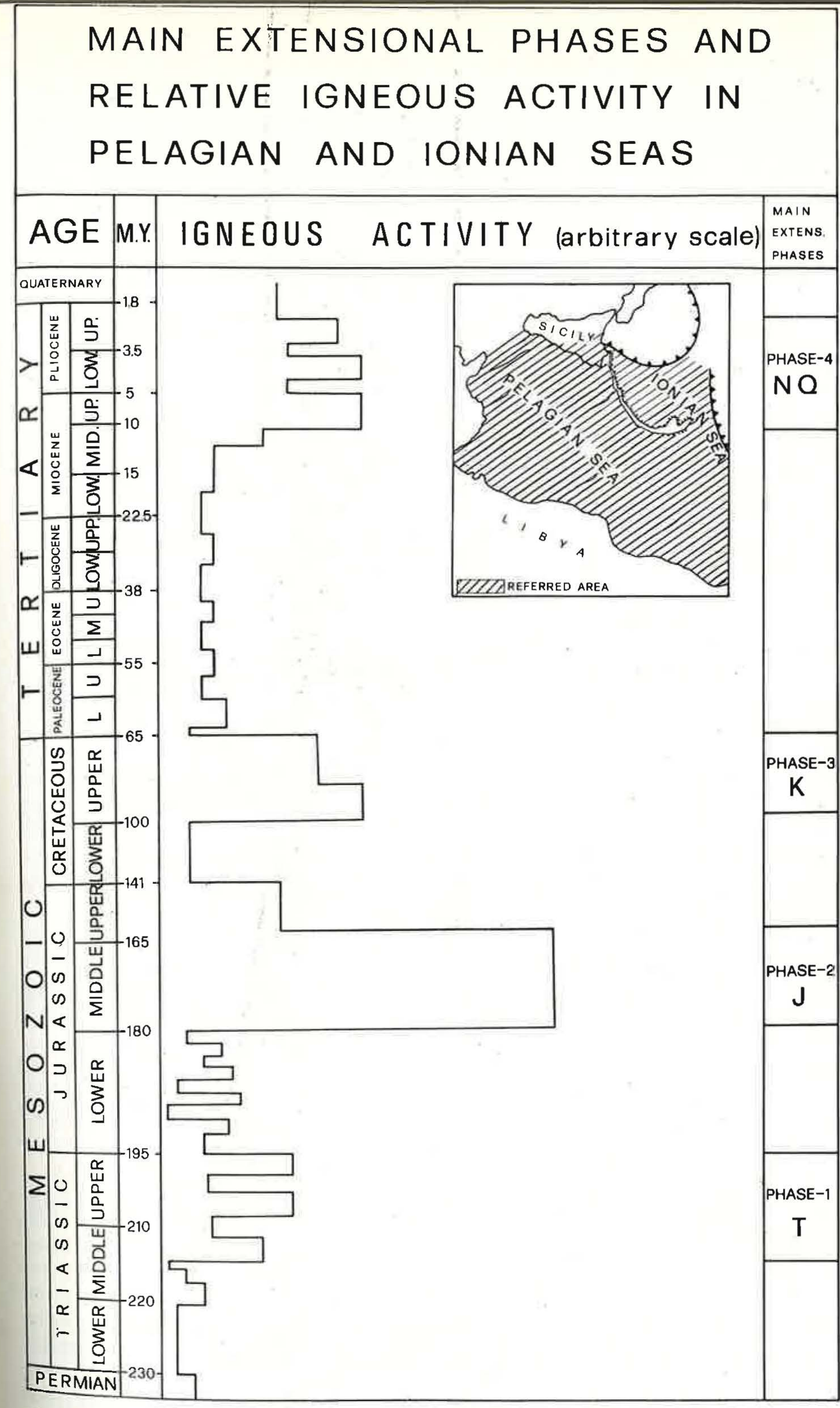


Fig. 32 — *Main Extensional Phases and Relative Igneous Activities of Pelagian and Ionian Seas.*

part of this province, such a time stratigraphic interval is completely or almost completely composed by igneous rocks. In Malta Island along the Sicily-Malta escarpment Middle Jurassic volcanic rocks are found. Also on the deeper part of the Sirte rise this volcanic phase can be expected.

The existence of volcanic rocks of the Middle-Upper Cretaceous phase are proven in the following areas: Gabes-Tripoli-Misurata Basin; Sicily-Malta plateau area. Geophysical evidence of "K" phase volcanism can be clearly recognized in the Sirte rise and very probably in the eastern Medina bank, and in the Ionian abyssal basin too.

The last Neogene-Quaternary phase ("NQ") with maximum activity in Middle-Upper Miocene to Quaternary is the most widely diffused and generalized one. Proven "NQ" igneous rocks exist in Ragusa and Sicily-Malta area, and mainly in the Pantelleria-Linosa-Medina grabens area: basalts of Lentini; volcanoes of Pantelleria and Linosa; volcanics of the Medina Graben of *Fig. 9*. But, other numerous volcanic shows, all along with the rifting area of the Sicily Channel are evident from seismic and magnetic data. Clear and reliable seismic evidence of "NQ" volcanic activity is recognized in the Sirte rise, Medina Channel, Sicily-Malta escarpment. Impressive volcanic bodies are recognized in the Ionian abyssal basin *(Fig.s 14, 15, 16 & 17)*. The most important one is that of the Marconi sea mount area *(Fig. 17)* where the thinnest crust conditions of the Ionian Sea exist.

4. Geodynamic evolution

In recent years, several plate tectonic models of evolution of the Mediterranean or part of it have been proposed by different Authors. Some of these are mentioned in paragraph 1. It is not the purpose of this paper to propose a new model or to analyze those already proposed and how they fit with the numerous regional data and conclusions here described. We wish only to observe that several basic propositions contained in some geodynamic models like, for example, in those of Biju-Duval et al., (1977), Laubscher et al., (1977), Scandone et al., (1976), and other Authors, are supported by relevant controlled data and arguments.

In the following, in greater detail, the most important geodynamical phases and corresponding deduced evolutive modifications of the investigated area, from the Permo-Triassic to the present, are commented on.

4.1 — Main extensional phases

As already mentioned in previous paragraphs, four main phases of geodynamical extensional activity, in the Central Mediterranean, from the Middle-Upper Triassic to the Quaternary, are recognized. These phases, obviously, correspond to those of the main volcanic activities:

1) Middle-Upper Triassic phase ("T")
2) Middle-Jurassic phase ("J")
3) Middle-Upper Cretaceous phase ("K")
4) Neogene-Quaternary phase ("NQ")

Analysis of extensional movements is limited to the northern part of the African plate and marginal basins.

4.1.1 — The Triassic continental rifting

Using in priority all numerous land or shallow water marine data available, utilizing also the relevant geophysical exploration of deep water on the Ionian Sea, it is possible to arrive at the fairly controlled conclusion that from the Late Permiam to the Lower Triassic, sedimentation took place on the northern continental margin of Africa in a substantially quiet geodynamical condition.

In the Middle Triassic the first recognised extensional phase, which continued also during the entire Upper Triassic, commenced its activity. In particular three areas have been stretched and deformed by this "T" phase *(Plate IV)*:

a) Gabes-Tripoli-Misurata basin
b) Streppenosa trough on Ragusa-Malta area
c) Sicily-Malta-Medina mounts escarpment

The Gabes-Tripoli-Misurata basin already existed during the Paleozoic, when the Gafsa-Jeffara extensional fault system originated. During the Middle Triassic this basin was newly stretched with consequent subsidence and expansion.

From the southern part of the Ragusa platform to the Malta area, before the "T" phase, in the Lower Triassic, a generalized platform carbonate sedimentation took place. This original platform was stretched and rifted so as to produce a regional trough *(Plate IV:* Streppenosa trough), where sedimentation assumed the characteristics of restricted pelagic condition ("Streppenosa" Fmt., or Black Shale). Part of this pelagic sedimentation, was probably involved in the successive crustal opening of the Middle Jurassic, and drifted away. The Sicily-Malta-Medina mounts escarpment and the Lower Sirte slope, were also affected by the same extensional geodynamics. The numerous basaltic interval existing in the Ragusa-Malta area on the Middle-Upper Triassic support this hypothesis. Locally, movements continued also in the lower part of the Lower Jurassic, but, in general, diminished drastically or ceased almost completely at the end of the Triassic.

This "T" phase produced an important rifting process that, probably, stopped at the continental stage with wide seaways, thinnings, and subsidences. This opinion is favoured by several Authors: Biju-Duval et al., (1977); Scandone (1976); Hsü (1978), and others.

4.1.2 — The crustal opening of Ionian Sea and Eastern Mediterranean in Middle Jurassic

During the Middle Jurassic along with the Ionian-Eastern Mediterranean marging of the African plate, the most important extensional phase, testified by prominent volcanic activity, occurred in the Central-Eastern Mediterranean. More specifically, on the Sicily-Malta-Medina Mounts escarpment area and on the deeper part of the Sirte rise, the extensional phase "J" performed the complete opening of the Ionian Sea. It is impressive to note that this crustal opening is to the opening of the South Atlantic Ocean.

In the Ragusa-Malta plateau area, particularly on its eastern part, the Middle Jurassic interval consists almost completely or only of igneous rocks. The magnetic anomaly map indicates that this controlled "J" volcanic activity of the eastern Ragusa-Malta plateau, very likely, extends on the Medina mounts area and on the Lower Sirte rise.

During this phase, the Apulian platform together with the whole Adriatic plate, which were already separated from Africa by a wide sea channel, during the previous phase "T" moved consistently far away northeastward. The Sicily-Malta-Medina mounts steep escarpment separates the continental crust of the Ragusa-Malta plateau from the oceanic crust of the Ionian abyssal basin *(Fig. 6)*. A scheme of crustal relationships between the two areas is given in *Fig. 33*.

Southeast of the Medina Mounts, the transition from continental crust to oceanic conditions, across the stretched, thinned, and subsided Sirte rise is much more progressive than across the Sicily-Malta escarpment. In fact, across this escarpment, at top Mesozoic *(Plate III)*, we pass directly with a mega-fault system from 0.5 ÷ 1.4 seconds reflection time of the plateau area to the value of about 7.0 seconds of the abyssal basin in

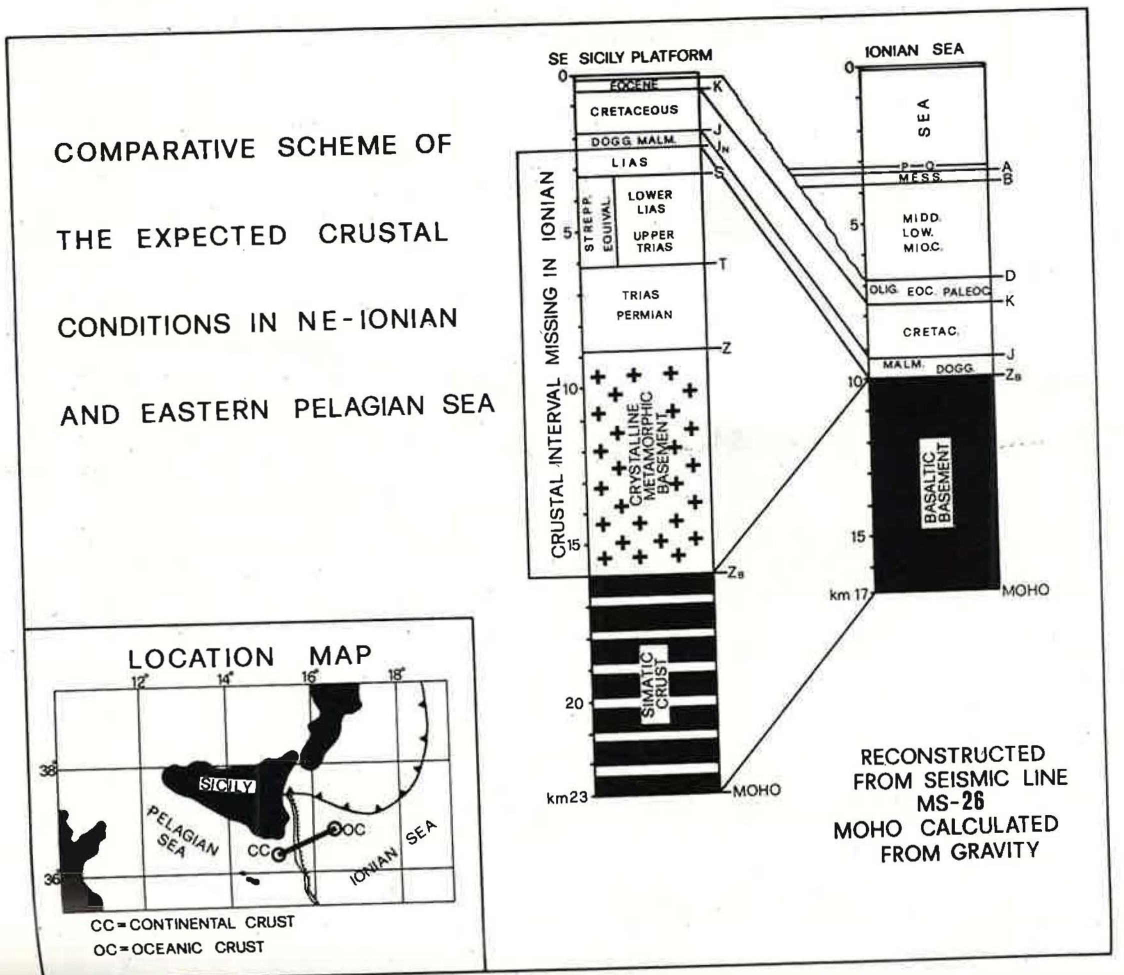


Fig. 33 — *Comparative Crustal Scheme of Pelagian Sea (Ragusa-Malta Plateau Area) and Ionian Basin.*

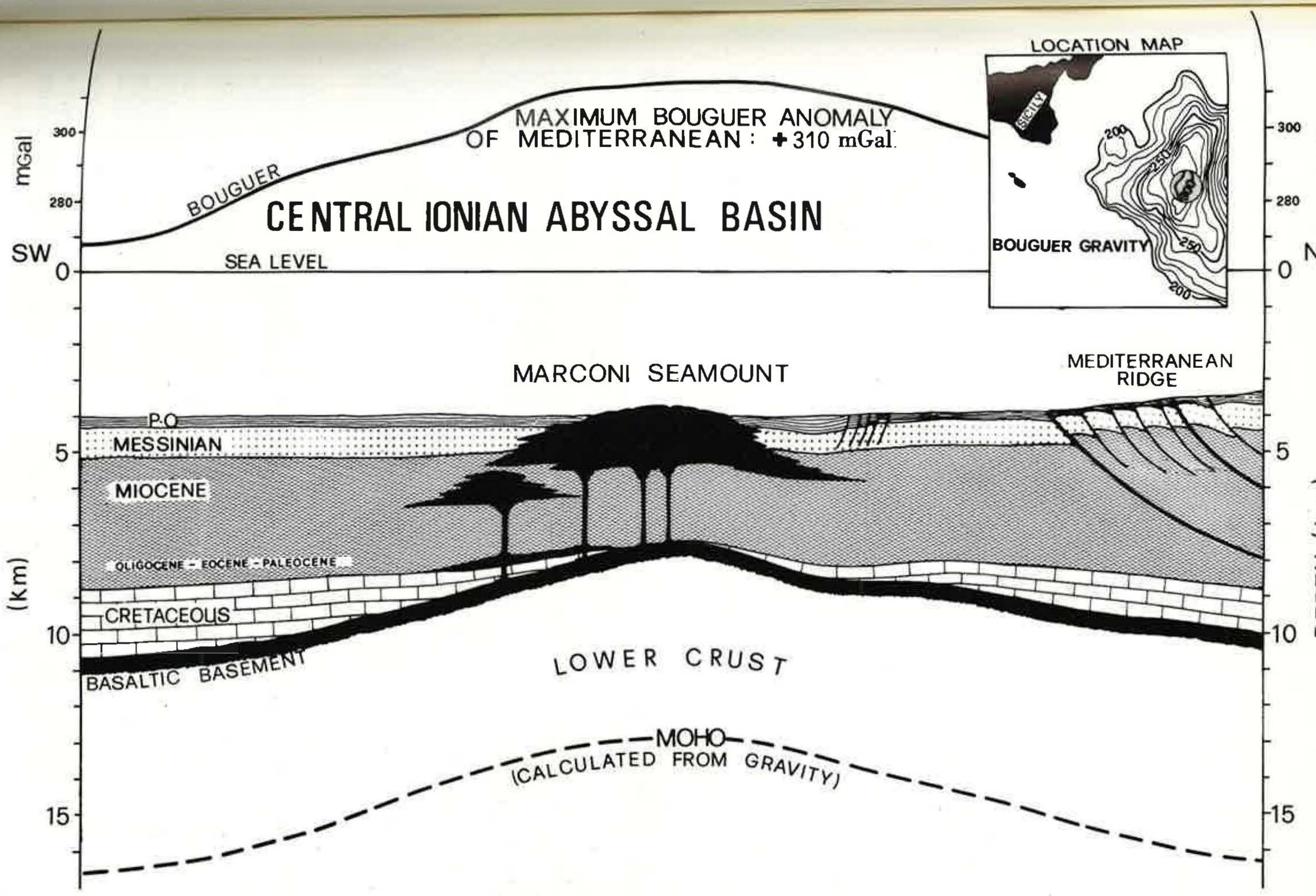


Fig. 34 — *Crustal Scheme of "Marconi Sea Mount" Area on the Maximum Mediterranean Gravity Anomaly.*
Basaltic basement remarkably uplifts and sedimentary sequence becomes much thinner. Prominent volcanic activity of "NQ" and very probably older phases.

only some 20 to 30 km. South of the Medina mounts the transition from shallow continental shelf to the Ionian abyssal basin takes place across the wide area of the entire Sirte rise, where completely different tectonic deformation occurred during the various geodynamical phases. East of the Medina plateau, for example, there is the Medina escarpment mostly due to the "K" and "NQ" stretching phases. This escarpment cannot be correlated with the Ragusa-Malta escarpment because of the enormously different dimensions and geological conditions. If we want to look for the southeast continuation of the equivalent tectonic feature of the Ragusa-Malta-Medina mounts escarpment, we can find it in the area from the Lower Sirte slope to about the 7.0 seconds reflection time *(Plate III)* at top Mesozoic. This area, now characterized by an intermediate crust type, very close to ocean like conditions, was greatly stretched during the "J" phase and, probably also during the "T" one. Successive "K" and "NQ" phases contributed to stretch the entire Sirte rise area and again the lower slope and deeper area above mentioned.

Therefore, any tentative correlation between the Ragusa-Malta escarpment and the Medina escarpment has very scarce geological meaning, because there is a much more significant correlation between the Ragusa-Malta-Medina mounts escarpment and the lower Sirte slope area *(Plate III)*. The Medina mounts, after the various geodynamical deformations that passed through show now a complex extensional tectonics with several fragmented blocks and collapsing faults having two main trends: E-W and NE-SW. Some shear faults seem to occur too.

4.1.3 — Stretching Cretaceous phase and associated prominent transgression

From the end of the Middle Jurassic to the Lower Cretaceous included, no remarkable and diffused volcanic activity or crustal movements seem to have affected the studied area, except for an evident subsidence in the Early Cretaceous (Neocominan transgression).

At the end of the Lower Cretaceous, a relatively thin, widely diffused marly interval ("Marne a Fucoidi" layer) all over the studied Central Mediterranean area, interbedded in carbonate sequence, occurs. This layer is characterized by a good and continuous seismic reflector and is probably associated with a subsidence or with a sea level uplift. Extensional geodynamic movements with subsidence and a remarkable transgression characterize the Upper Cretaceous (Cenomanian transgression) which is very prominent in the Northern Africa area, but is also evident in the Apulian and Adriatic areas. Thus, the "K" phase of our scheme of *Fig. 32* produced stretching, faulting or activation of existing faults, subsidence, and magmatic activities of a basaltic or pyroclastic type in several parts of the Central Mediterranean.

In the Gabes-Tripoli-Misurata basin there is clear evidence of extensional tectonics with faulting and basaltic effusions widely distributed in the Late Cretaceous. Volcanic activity of the "K" phase is also found in the Ragusa-Malta plateaus area and more sporadically in other parts of the Pelagian Sea. Evidence of tectonic and volcanic activity of this phase exists also in the Ionian abyssal basin.

But, the geological province where the "K" phase seems to have produced its most remarkable effects is that of the Sirte rise and the Sirte basin. In the Sirte rise the stretching activity is proved by the existence of numerous faults with back-tilted blocks and volcanic effusions of clear Upper Cretaceous age. This geodynamics produced a consistent subsidence of the whole Sirte rise and of the Sirte basin, and a remarkable marine ingression on the north African plate. Apulia continued its moving away.

4.1.4 — The Miocene-Quaternary phase and the huge rifting of Sicily Channel

The last extensional phase was active from the Middle Upper Miocene to the Quaternary. It is possible to recognize volcanic extrusions in many zones of the Pelagian and Ionian Seas. Well known volcanoes are those of Pantelleria and Linosa Islands. Volcanic outcrops associated to this phase exist in the Ragusa area (Basalts of Lentini, etc.).

The seismic evidence of faulting and of igneous bodies of the Neogene-Quaternary age is identified on several sites of the Pantelleria-Linosa-Malta-Medina grabens area. See *Fig. 9* for example. Other shows are found in the Sicily-Malta escarpment *(Fig. 6)* and south of the Medina mounts *(Fig. 7)*.

Very clear seismic evidence of "NQ" volcanic activity and faulting exists in numerous points of the Ionian abyssal basin *(Fig.s 14, 15, 16 & 17)* and of the Sirte rise.

All these data show that the "NQ" phase produced its effects on a vast part of the studied area. However the area where this phase determined the most remarkable geological, geomorphological and even crustal modifications is that of the Pantelleria-Linosa-Malta-Medina grabens, or the area of the impressive rifting of the central Pelagian Sea, called globally "Sicily Channel" *(Fig. 1)*.

The rifting process of the Sicily Channel is more developed in the area from Pantelleria-Linosa to Malta *(Fig.s 11, 12 & 13)* than at the NW extremity of the Pelagian Sea between Cape Bon in Tunisia and Mazara del Vallo in SW Sicily. Also along with the Medina graben the process is not so impressive as that shown on the seismic line MS-19. But the Sicily channel rifting area is continuous all along the entire Pelagian Sea from the Tunisian extremity to the Ionian Sea.

Seismic, gravity and magnetic data show clearly that the rifting, still active, has already produced a remarkable geological deformation involving not only the entire sedimentary sequence, but remarkable tilting movements on both sides of the Sicily channel area show that also the Lower crust participates in the geodynamical processes with uplifting of the earth's mantle. Bouguer gravity *(Fig. 2)* confirms this observation. In fact along the Sicily Channel there is a remarkable positive regional anomaly which, probably, is associated with a crustal thinning produced by the "NQ" stretching phase. It can be said that the rifting process has already evolved to such a stage as to practically now divide the Pelagian Sea essentially into two separated blocks. One to the north is formed by the Adventure and Ragusa-Malta plateaus and the second one on the south is formed by the Lampedusa and Medina plateaus. This second block remains substantially connected to the North-African plate, because even though it is affected by several extensional faults and grabens, these are much less important than those of the Sicily Channel.

The Apulian (Adriatic) plate has continued to move more moderately away from the African one and during this period its SE passive margin, in the Ionian Sea, has been affected by numerous new extensional faults or activation of previously existing ones. This extensional process is still active. A very high seismicity in recent and/or historical time has been observed along with the Kefallina and the Gargano regional transcurrent faults. Examining these data and the deformation pattern of the whole area surrounding the Apulian plate (Apennine, Dinarides, and Hellenides) it seems possible to argue that the Apulia is now moving anticlockwise along with the above mentioned Kefallinia and Gargano faults.

4.2 — Compressional phase of Calabrian and Hellenic Arcs

In the Lower-Middle Miocene, the North African Margin commenced to collide with the southern margin of the European plate. In particular the north Sicily margin disappeared beneath the European south-moving overthrusts.

At the same time the inner Calabrian arc composed by European blocks moved outward (SE) and overthrusted the Ionian abyssal basin Crust. The Taormina transform fault has played an important role in this process.

The final result is a tectonically complex orogenic arc with overthrusts, reverse faults, repeated imbrication of blocks and gravity sliding *(Fig. 19)*. In the Ionian the sediments covering the paleo-oceanic Crust of the African margin are scraped with a shearing plane that progressively deepens towards the inner arc.

According to our interpretation, the accretionary zone, out of the European thrusted one, is composed by sediments from the Middle-Upper Jurassic to the Quaternary.

The Hellenic arc shows a deformational scheme similar to that of Calabria. On its Ionian side the compressional movements and the relative deformations are much clear than on the Levantine one.

As already observed in the Calabrian arc, also in the Hellenic one, the first deformational process, at the limit with the undeformed Ionian abyssal basin, is due to an imbrication of blocks of Messinian to Plio-Quaternary rocks over a shearing plane which corresponds to the base of the Messinian salt *(Fig. 26 & 28)*. Then the overthrusting progressively involves older sediments and the shearing plane deepens *(Fig.s 27, 29 & 30)*.

From seismic data a regional geological section across the Ionian abyssal basin and the whole Mediterranean ridge has been reconstructed *(Plate II)*. The feature of the Mediterranean ridge, substantially, constitutes the fore-arc scraping zone of the Hellenic arc. It is formed by imbrication of blocks which include sediments sheared from the paleo-oceanic basement of the subducting African plate. If the deduced time of crustal opening of the Ionian (and the Eastern Mediterranean) is correct, here too, as in the outer Calabrian arc, the oldest sediments involved in the thrusting process would be those of the Middle-Upper Jurassic, but the existence of fragments of the opened African continental crust, including the Permo-Triassic and the Liassic, cannot be completely excluded.

The seismic stratigraphy clearly indicates that between a block and the previous or the successive one of the scraping zone of the Mediterranean ridge there is generally a possible correlation, while the Hellenic trench separates two zones completely different from the viewpoint of the seismic characters. This is perfectly comprehensible if it is assumed that the Hellenic trench is the regional tectonic contact between the subducting African plate and the European one.

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BOOKS REVIEW

J.D. Byerlee and M. Wyss (Ed): ***Rock friction and eartquake prediction.***
Contributions to Current Research in Geophysics (CCRG) 6. Birkhauses, Verlag, Basel und Stuttgart.

This is the special volume 116 n. 4-5 of Pure and Applied Geophysics and consists of 26 papers, most of which were presented at the Conference "Experimental studies of rock friction with application to earthquake prediction" held at Stanford University on April 28-30, 1977 and were integrated with suggestions arisen during the discussion at the congress.

The mechanics of the rocks under stress and the theory of dilatancy is of course the subject of the majority of papers and many experimental results obtained in laboratory are described.

Four articles at the beginning give a general description of the argument and they can be considered as reviews of selected topics.

A number of papers describes the relation between friction and rocks type, temperature, sliding rate, presence of water and the character of the sliding surface. Heat flow anomalies along active faults, such as the San Andreas fault, are compared in some articles with the laboratory measurements of friction and the formulated considerations are interesting. The temperature increase during frictional sliding is presented together with the results of some experiments.

The problem of the premonitory change in the seismic velocity through seismic regions is very important in earthquake prediction. The results obtained in California lead to some considerations about the precision required in the readings of the first arrivals. All the conditions of stress, pressure, temperature and pore pressure have to be investigated to study completely the problem of the velocity changes.

Other anomalous variations in physical properties reported sometimes before large earthquakes, such as in electrical resistivity, and in magnetic susceptibility as well as premonitory slip and gas emission have been studied in some laboratory experiments, and the results are shown.

The variations in dilatancy and permeability during changes in stress on rock were investigated in laboratory and some works are described.

Theoretical and experimental studies about particle and rupture velocity, modes of slip during fracture and frictional sliding and radiation of seismic waves are also presented in some papers.

The volume results in a rather complete presentation of the aspects connected with the subject of the rock friction.

Dario Slejko